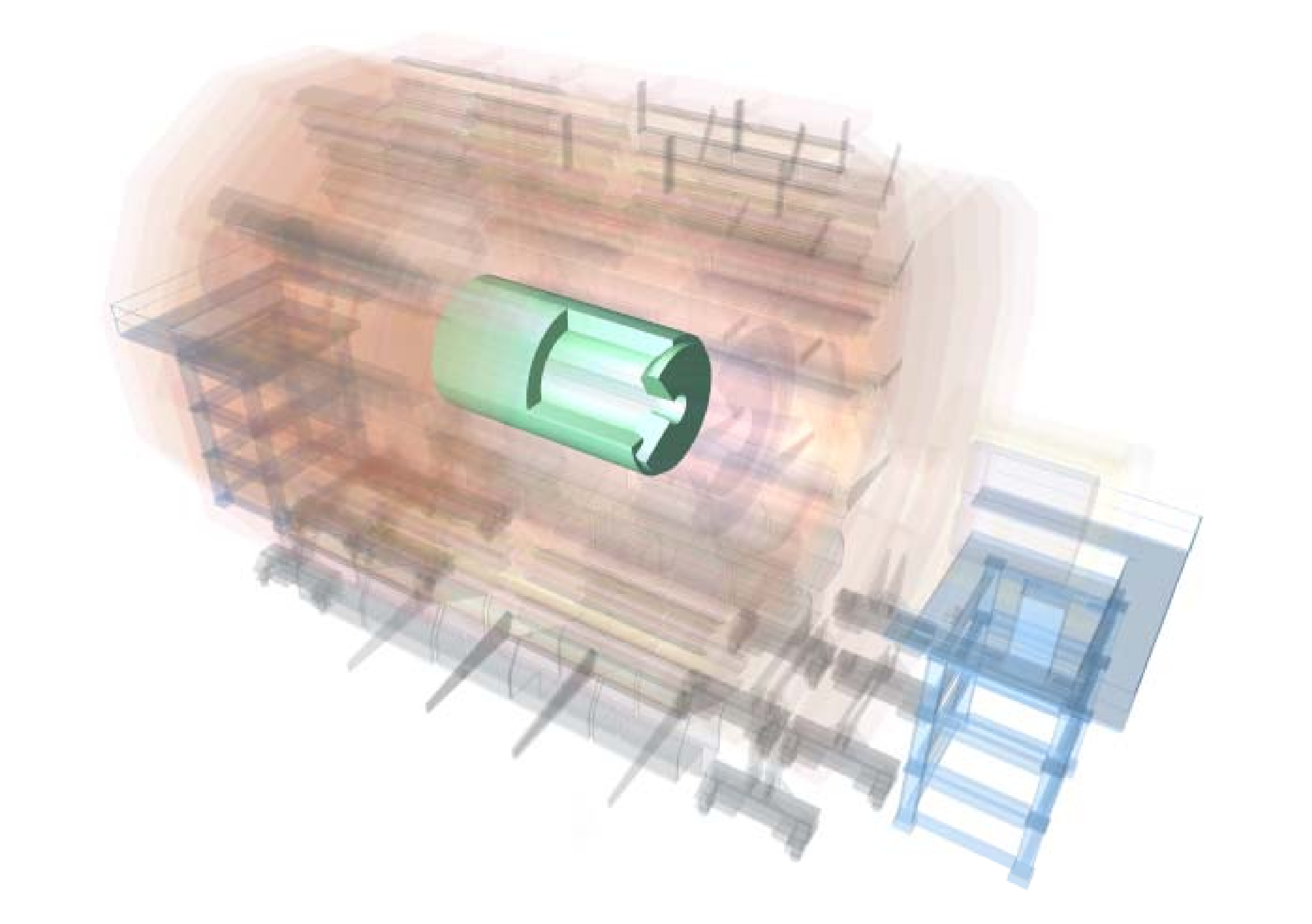
Electromagnetic Calorimeter



Why Crystals?

Crystal Calorimeters have been used in HEP experiments:

- for precision energy measurements of e, γ, π^0, ...
- to help in position measurement.

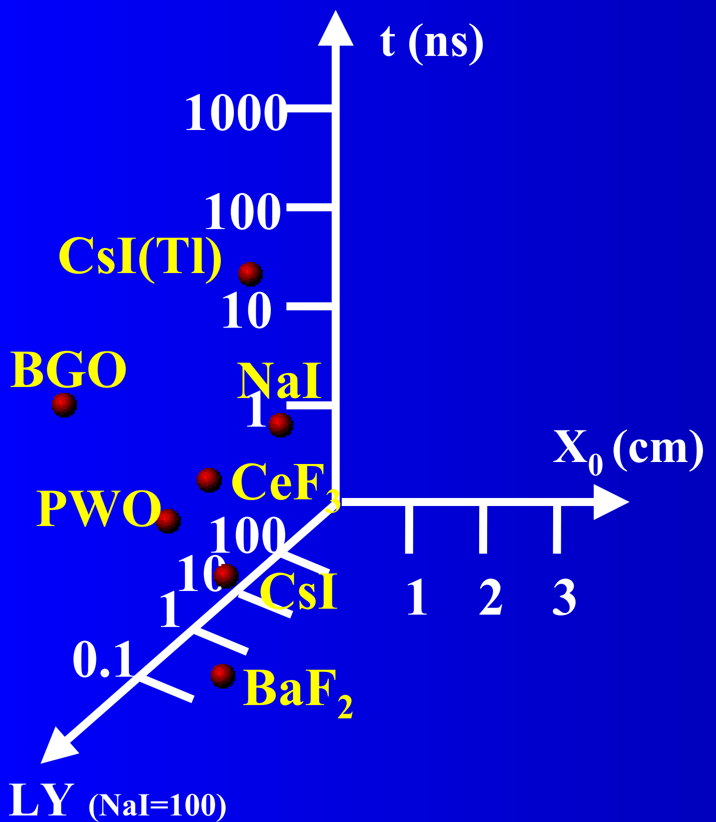
- Calorimeters
  - Sampling — Sample fluctuations degrade E resolution
  - Homogeneous
    - Cerenkov — Low light yield
    - Scintillators
      - Plastics
      - Warm Liqs. e.g. toluene
      - Noble Liqs.
      - **Crystals**

X_0 too long to be practical (factor of 2 - 20 w.r.t. crystals) excl. LiXe (availability, purity)

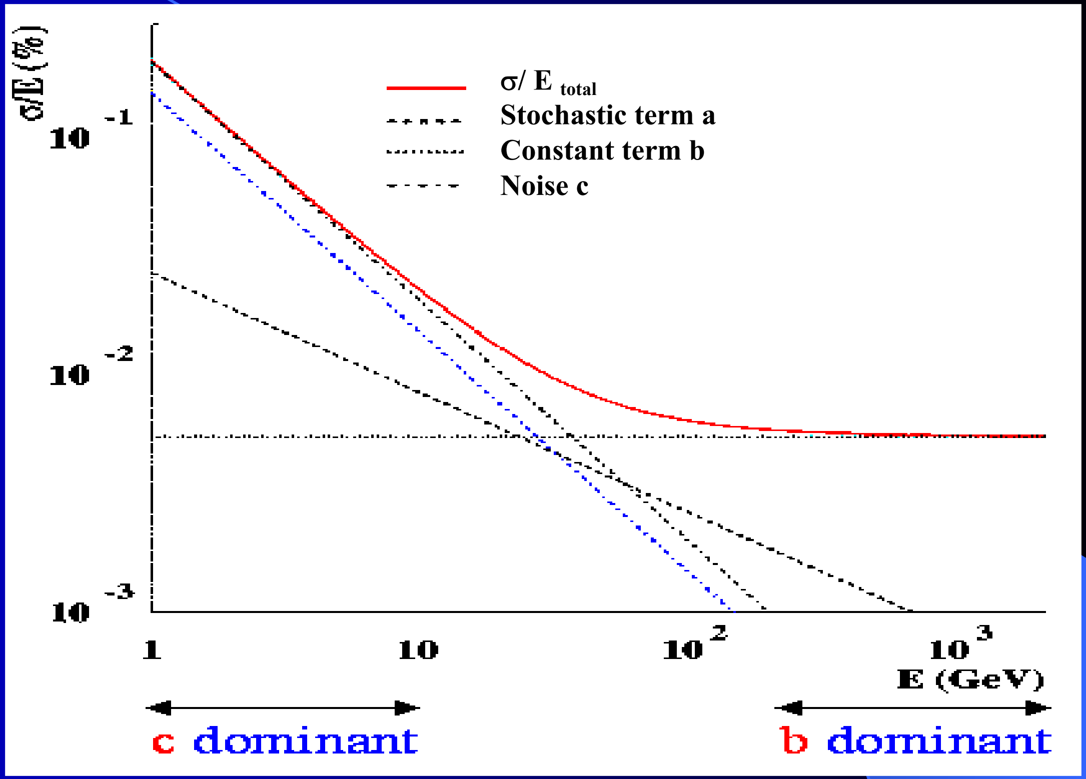
Which Crystals?

Design Issues

A calorimeter design 'phase space':



Focus on energy resolution:



$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

Other Factors:

- Production (machining, raw material available)
- Appropriate photodetector exists (=f(LY,B))
- Experimental conditions (rad. environment,cost)
- Ability to manage temperature dependence

Crystal Comparison

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	CeF_3	BGO	$PbWO_4$	LSO(Ce)	GSO(Ce)
Density (g/cm^3)	3.67	4.51	4.51	4.89	6.16	7.13	8.30	7.40	6.71
Radiation Length (cm)	2.59	1.85	1.85	2.06	1.68	1.12	0.90	1.14	1.37
Molière Radius (cm)	4.8	3.5	3.5	3.4	2.63	2.3	2.0	2.3	2.37
Interaction Length (cm)	41.4	37.0	37.0	29.9	26.2	21.8	18	21	22
Refractive Index [a]	1.85	1.79	1.95	1.50	1.62	2.15	2.20	1.82	1.85
Hygroscopicity	Yes	Slight	Slight	No	Slight	No	No	No	No
Luminescence [b] (nm) (at peak)	410	560	420 310	300 220	300 340	480	560 420	420	440
Decay Time [b] (ns)	230	1300	35 6	630 0.9	25 8	300	50 10	40	60
Light Yield [b,c] (%) (Room temp.)	100	45	5.6 2.3	21 2.7	8	9	0.1 0.6	75	30
d(LY)/dT [b] (%/ °C)	~0	0.3	-0.6	-2 ~0	<0.1	-1.6	-1.9	?	?
Experiment	Crystal Ball	CLEO-II, BaBar, BELLE	kTeV	L*, GEM	L3P	L3	CMS, ALICE, ..	?	?

a. at peak of emission; b. up/low row: slow/fast component; c. measured by PMT of bi-alkali cathode.

CMS Crystal Calorimeter

Choice of crystal:
- LHC rate (25 ns)
- Radiation environment
- Longitudinal containment (X_0)

$PbWO_4$

	Effects	Barrel	Endcap/Preshower
a	Shower flucs. /Tr. leak. Sampling fluctuations Photodetectors	1.5% $GeV^{1/2}$ nil 2.3% $GeV^{1/2}$	1,5% $GeV^{1/2}$ 5% $GeV^{1/2}$ (Presh.) 2.3% $GeV^{1/2}$
b	Calibration LY Non -uniform. Rear shower leakage	0.4% 0.3% <0.2%	0.4% 0.3% <0.2%
c	Electronic noise Rad-induced dark current Pileup	150 MeV 30(110) MeV 30 (95) MeV	750 MeV 175 (525) MeV

Choice of photodetectors:
- $|B|=4T$,
- $PbWO_4$ Low room-temp LY

APD(Barrel),VPT (EC)

Energy resolution:

Barrel $$\frac{\sigma}{E} = \frac{2.7\%}{\sqrt{E(GeV)}} \oplus 0.55\% \oplus \frac{115\ MeV}{E}$$

Endcap $$\frac{\sigma}{E} = \frac{5.7\%}{\sqrt{E(GeV)}} \oplus 0.55\% \oplus \frac{770\ MeV}{E}$$

CMS Crystal Calorimeter

Choice of crystal:
- LHC rate (25 ns)
- Radiation environment
- Longitudinal containment (X_0)

$PbWO_4$

	Effects	Barrel	Endcap/Preshower
a	Shower flucs. /Tr. leak. Sampling fluctuations Photodetectors	1.5% $GeV^{1/2}$ nil 2.3% $GeV^{1/2}$	1,5% $GeV^{1/2}$ 5% $GeV^{1/2}$ (Presh.) 2.3% $GeV^{1/2}$
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Choice of photodetectors:
- |B|=4T,
- $PbWO_4$ Low room-temp LY

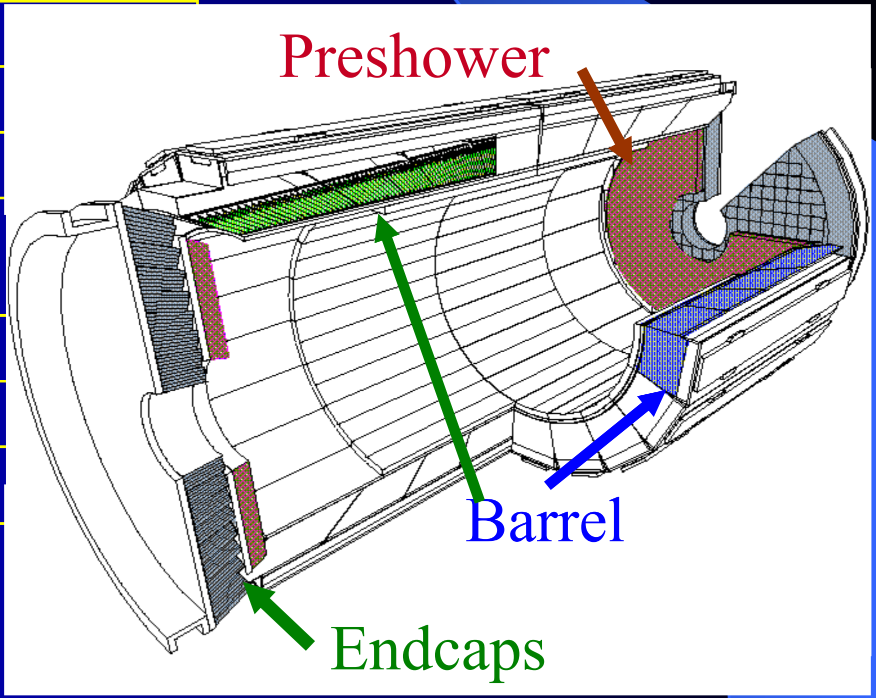
APD(Barrel),VPT (EC)

Energy resolution:

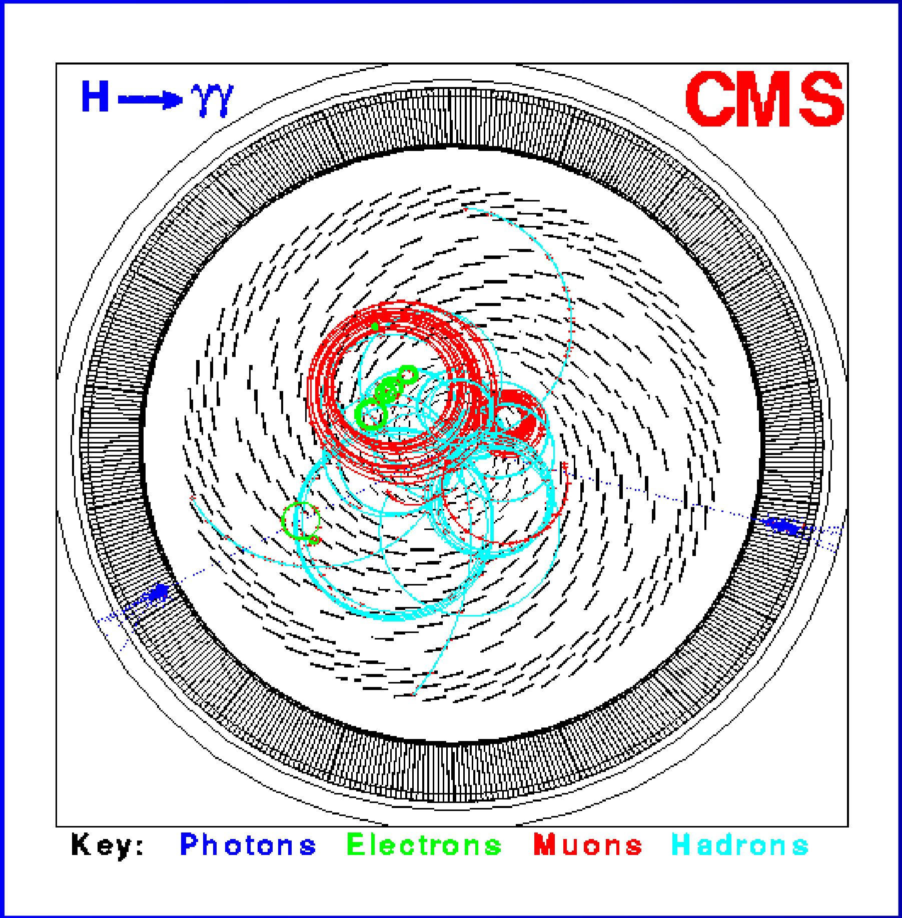
		1 GeV	10 GeV	100 GeV	300 GeV
Barrel	$\frac{\sigma}{E} =$	15.7 %	1.9 %	0.6 %	0.6 %
Endcap	$\frac{\sigma}{E} =$	77.2 %	7.9 %	1.1 %	0.7 %

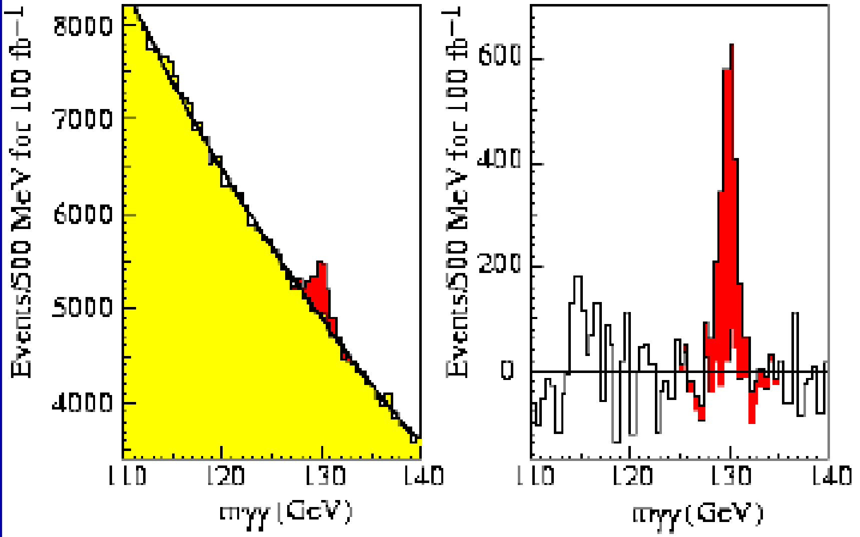
CMS Crystals

Parameter	Barrel	Endcaps
Coverage	$\lvert\eta\rvert < 1.48$	$1.48 < \lvert\eta\rvert < 3.00$
R_{inner}, R_{outer} (mm)	1238, 1750	316, 1711
z_{inner}, z_{outer} (mm)	0, ± 3045	± 3170, ± 3900
Granularity $\Delta\eta \times \Delta\phi$	0.0175×0.0175	0.021×0.021 to 0.050×0.050
Crystal Front Dimension (mm^3)	$21.8 \times 21.8 \times 230.0$	$29.6 \times 29.6 \times 210.0$
Depth in X0	25.8	23.0
Off – Pointing	3º	3º
Modularity	36 Supermodules	4 Dees
Crystals	1700 per SM (85 in η, 20 in ϕ)	3700 per Dee
Volume (m^3)	8.14	2.20
Weight (tons)	67.4	18.2
Number of Crystals	**61200**	**14600**



Expected Event Pattern and Signal
$H \rightarrow \gamma\gamma$





$m_H = 130$ GeV

Need fine granularity and high energy resolution.

Unprecedented Technical Challenges

Focusing only on a few central elements, nearly

77 000 large size, radiation hard PWO crystals,
130 000 radiation hard, avalanche photodiodes,
16 000 vacuum phototriodes

which qualify for being used for high precision measurements in a hostile environment for more than 10 years have never been produced.

Technical specifications, quality, stability, reliability, reproducibility, radiation hardness, and delivery schedule were of major concern.

On top of all, the detector must be affordable.

PWO History - Need for R & D for CMS

Lead tungstate ($PbWO_4$) first time introduced as material for HEP in 1992 at conference by Nagornaya (Kharkhov) and Katchanov (IHEP)

R&D in Crystal Clear collaboration at CERN since 1992

First growth technology developed by INP Minsk and transferred to Bogoroditsk at the end of 1992

$PbWO_4$ chosen as ECAL baseline by CMS in October 1994

Challenging problem at that time:
How to

technically develop
install production infrastructure
for the need of CMS

PWO Producers

Large efforts made in the field of crystallography in former Soviet Union, with availability of

- many highly skilled people
  - academic experts in all the fields related to crystallography
  - excellent technologists
- impressive crystal growth infrastructure installed in several plants, to produce large quantities of crystals for military applications.

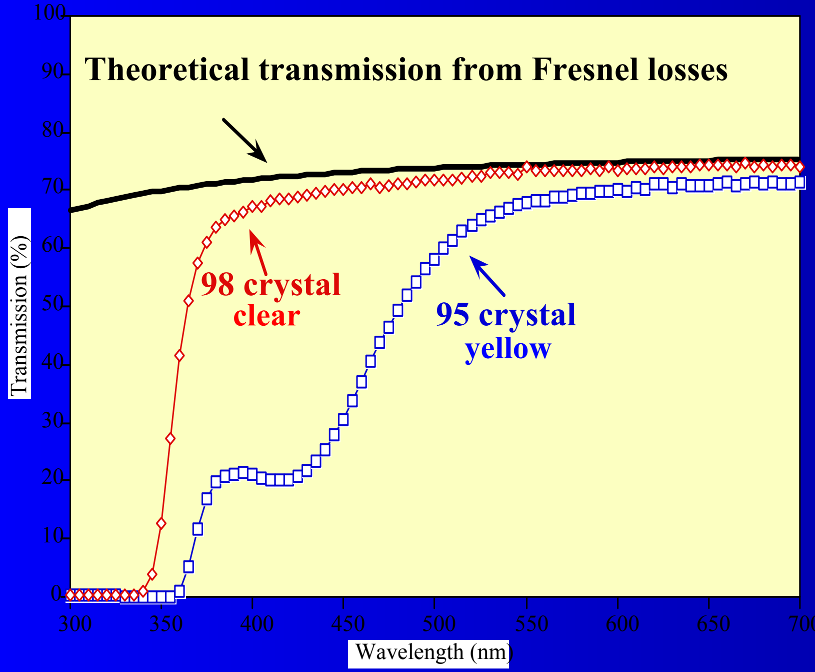
Once this situation has been understood and correctly evaluated, we have

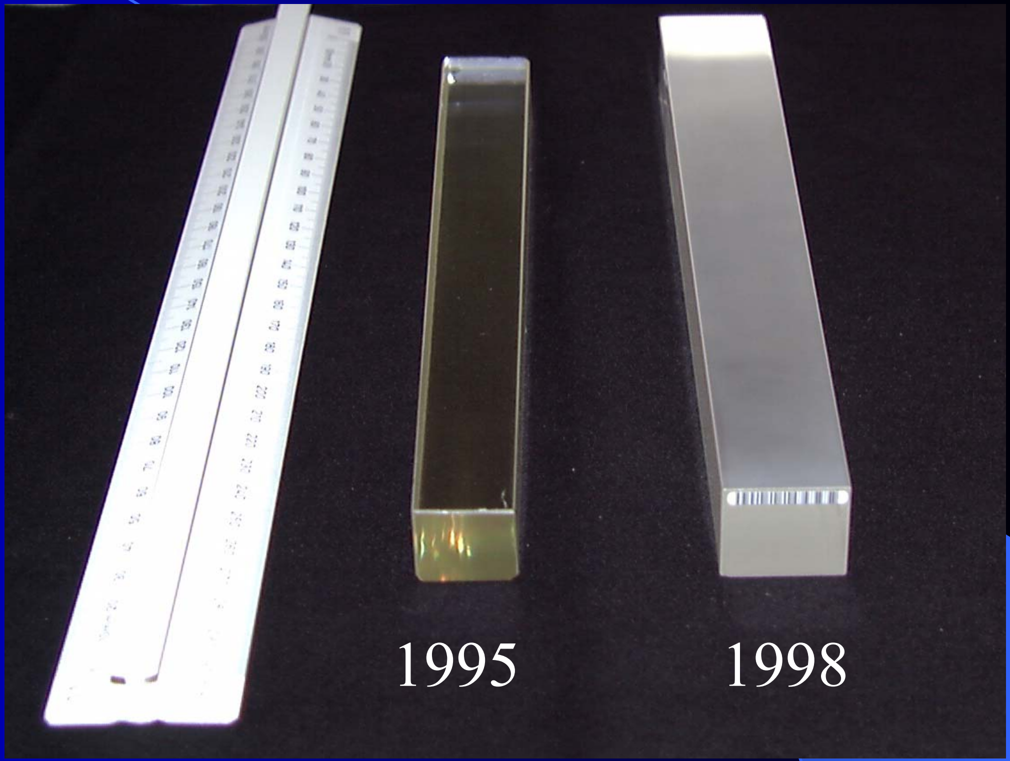
- selected the Bogoroditsk Techno-Chemical Plant after an audit of several companies
- started a fruitful collaboration with the International Science and Technology Centre ISTC.

PWO R & D for CMS - First Phase

July 1996 to July 1998
Demonstration of Principle:

Grow PWO crystals that reach the level of performance imposed by the very challenging requirements of CMS.





A few crystals were grown

Hans Rykaczewski
CERN & ETH Zurich

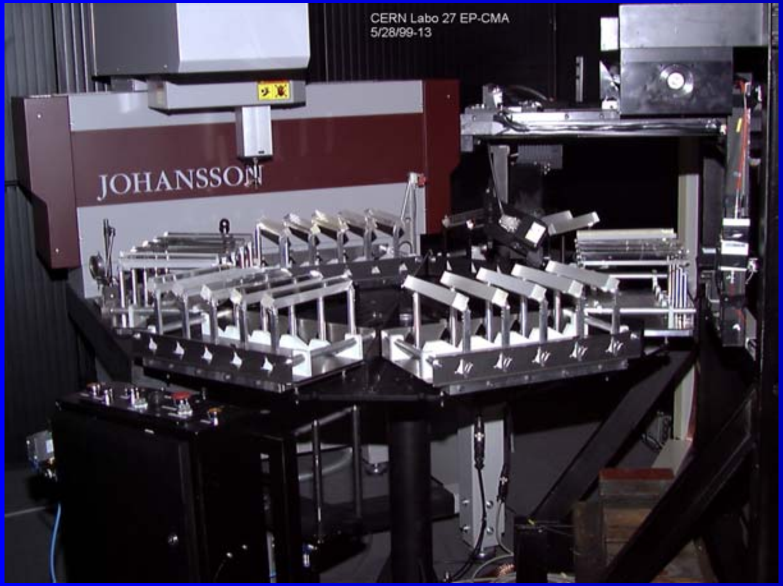
PWO R & D for CMS - Second Phase

July 1999 to July 2000

Develop Economical Technology:

Implement a production technology to mass produce PWO crystals with consistent quality at an affordable price.

The first 100 crystals at CERN



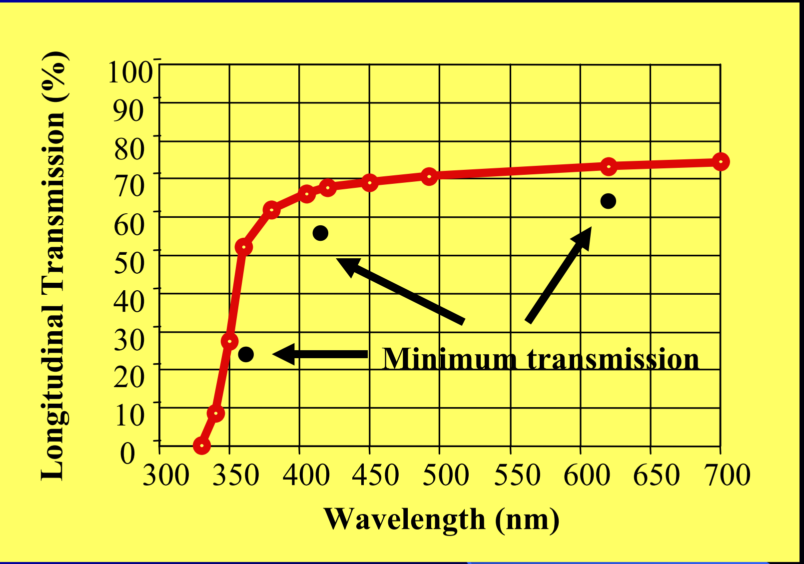
High Precision Photospectrometer

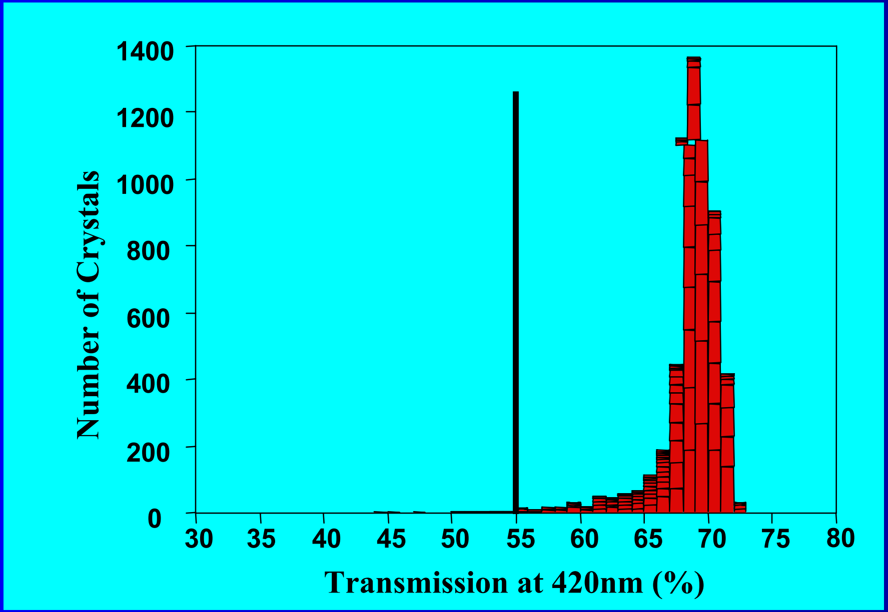
PWO R&D for CMS - Third Phase

Starting August 2000
organize a modern production structure:

Implementation of a modern industrial management

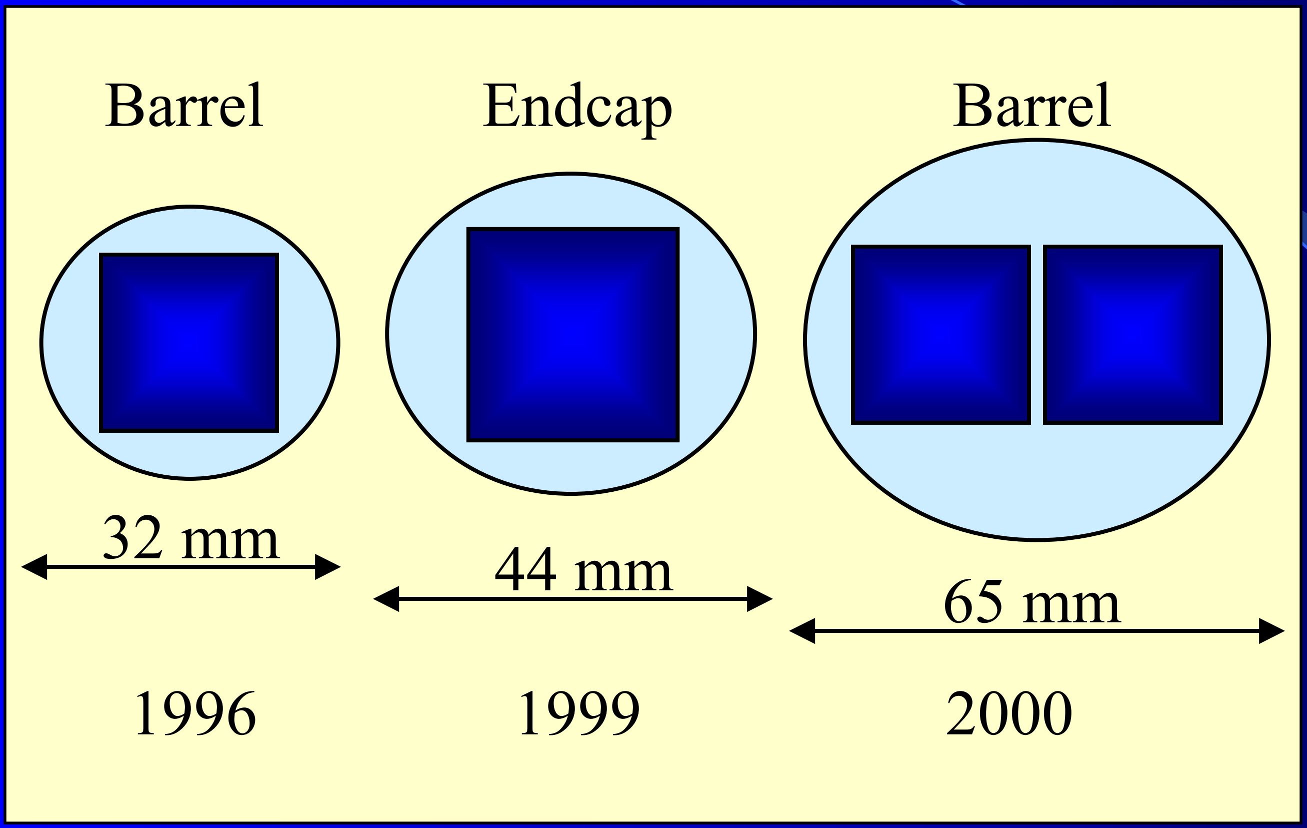
- implement a strict quality assurance policy
- install modern communication tools
- develop a marketing strategy

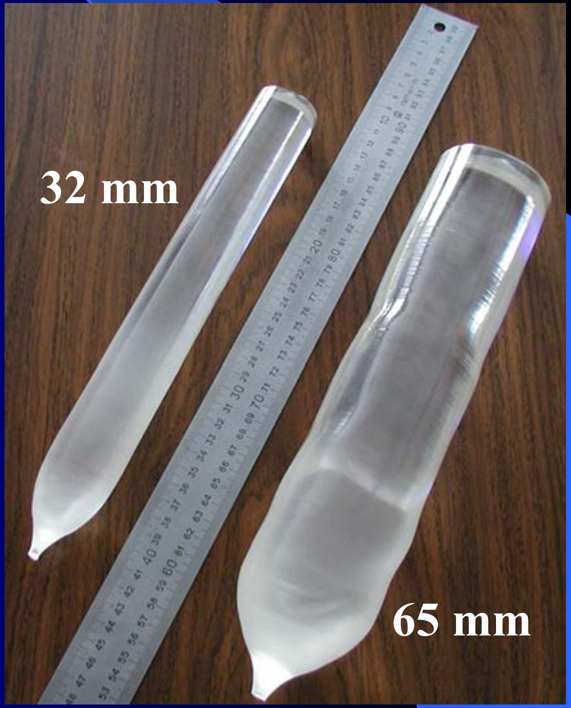




6000 crystals have been produced during the third phase

Ongoing Improvements for CMS Crystals





Larger and more crystals per ingot

Motivations for Further Increasing Ingot Diameter

Increase equipment productivity to damp possible variations in

- Electricity price
- Raw material price
- Taxes policy
- Manpower cost

Significantly increase the production capacity in order to

- add flexibility to the CMS production scenario
- cope with possible problems with other producers (schedule, quality, cost)
- be protected from other "competing" demands:

  Alice + BTeV + KOPIO + A NKE + CEBAF = 73000 crystals

Accomplishments in the Year 2002

Upgrade raw material production to more than 2 tons per month

Get platinum for 33 additional ovens now installed at the producer

Setting-up the technology for large ingots on 138 ovens

- 45 ovens – January 2002
- 90 ovens – March 2002
- 138 ovens – May 2002

Reorganize production schedule

Slow down production to allow the progressive upgrade of the 138 ovens to the large ingot technology.

Keep a minimum production to not affect the CMS construction schedule in both regional centers with a reasonable safety margin.

Progressively introduce the new wire cutting technology.

Resume production along a schedule compatible with the CMS schedule.

Message from Bogoroditsk
December 4, 2001

OFFICIAL MEMO To CMS

…

With big pleasure we inform you that Russian Federation President Mr. V. Putin by his ukase N653 on 28.11.01 allowed to Gochran to give in rent to our Plant Pt needed for 33 additional pullers and execution of the deliveries to Bogoroditsk.

…

Best regards

Kostylev

Annenkov

Upgrade of Ovens to Large Ingot Technology

- Change and tuning of pulling rod and seed holder
- Upgrade the crystal weight feedback system

- Replacement of RF coil
- Replacement of ceramic heat screens

Upgrade Large Ingot Technology

Replace 120 mm Pt crucible by new 170 mm composite Pt crucibles

Upgrade the Rf power cycle for heating, smelting, pulling and cooling.

Optimization of procedure for crystal ingot extraction from crystallization unit.

Upgrading Cutting Technology

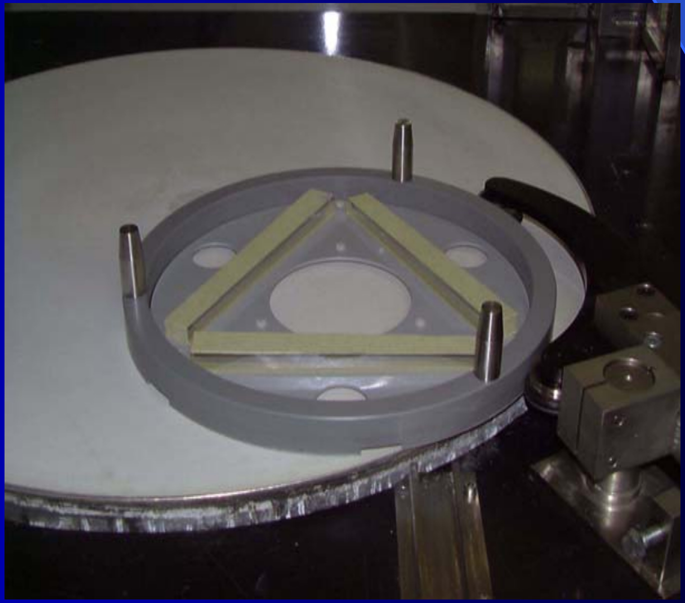
Old cutting equipment

Wire cutting machine from DIAMOND WIRE SYSTEMS, COLORADO SPRINGS, USA, installed in June 2002

Similar machines used by semiconductor industry for cutting wafers

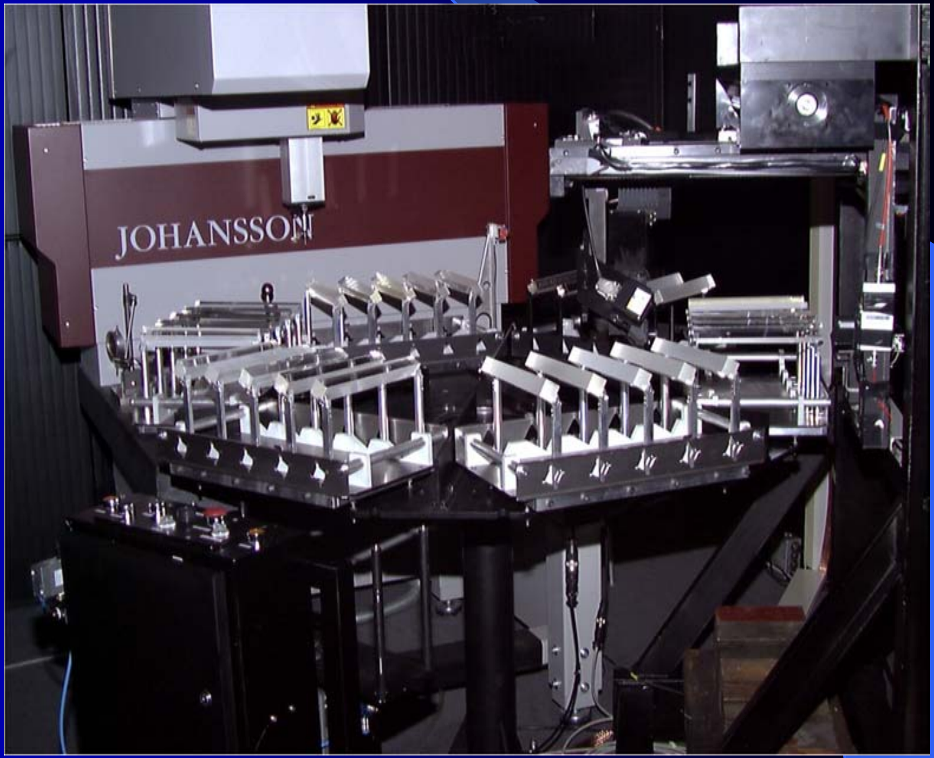
Upgrading Lapping and Polishing

Refurbished Russian equipment

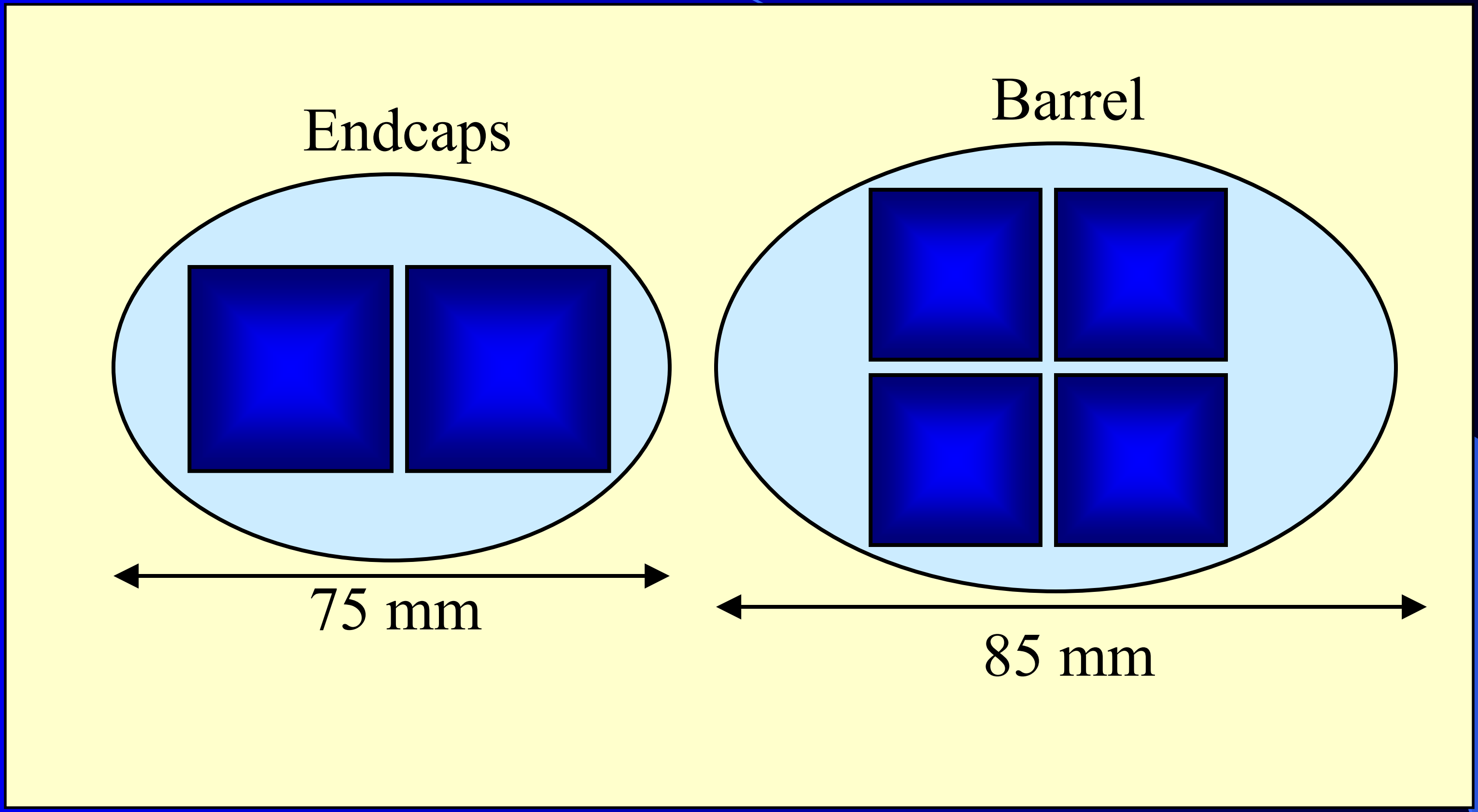


Crystal Quality Control

Identical quality control facilities are set up
at the producer's site and
at the Regional Center at CERN



Present Developments

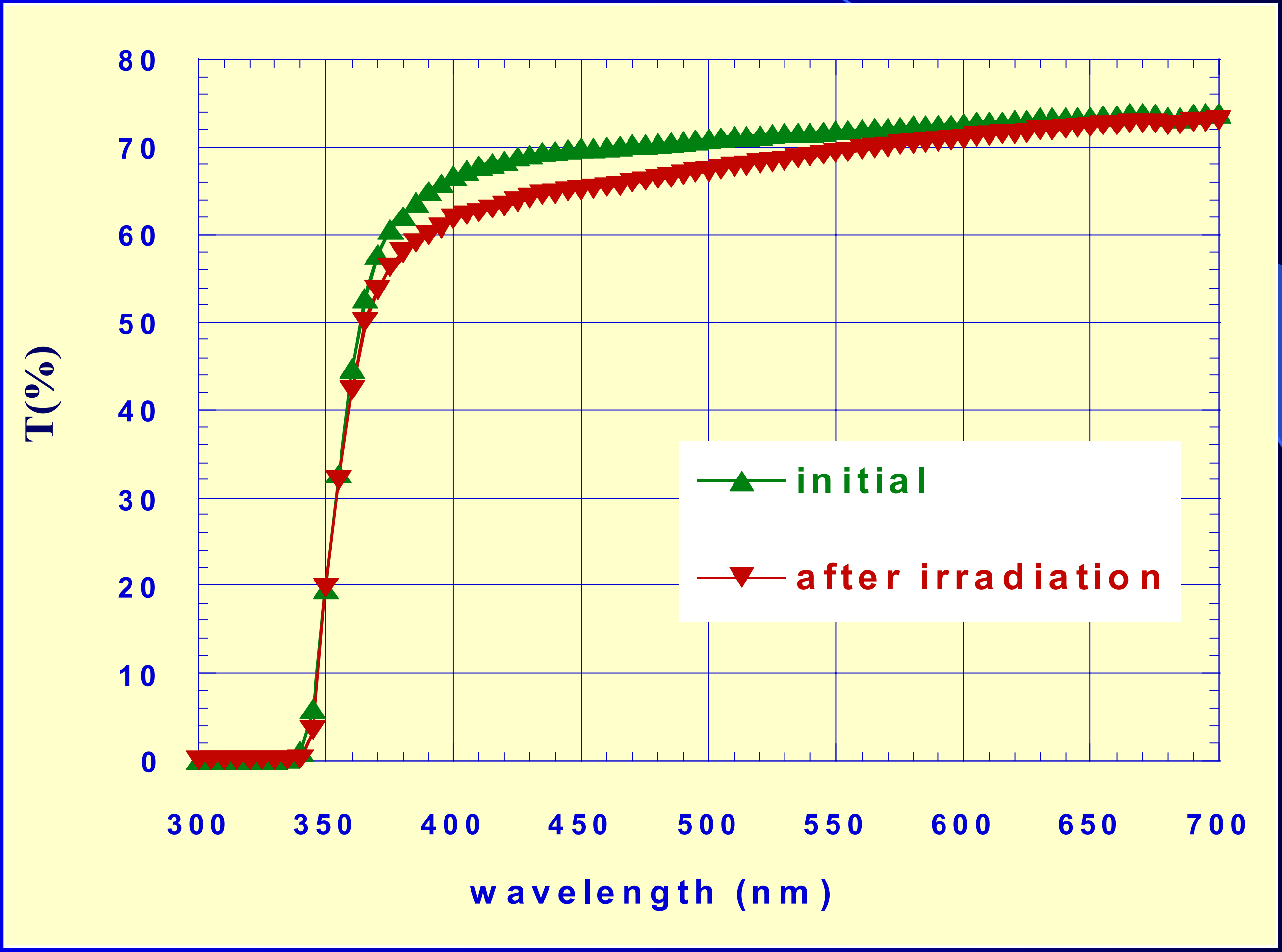


Promising initial results.
Gives contingency to CMS production schedule.

Parameters to Qualify Crystals
Some Basic Technical Specifications

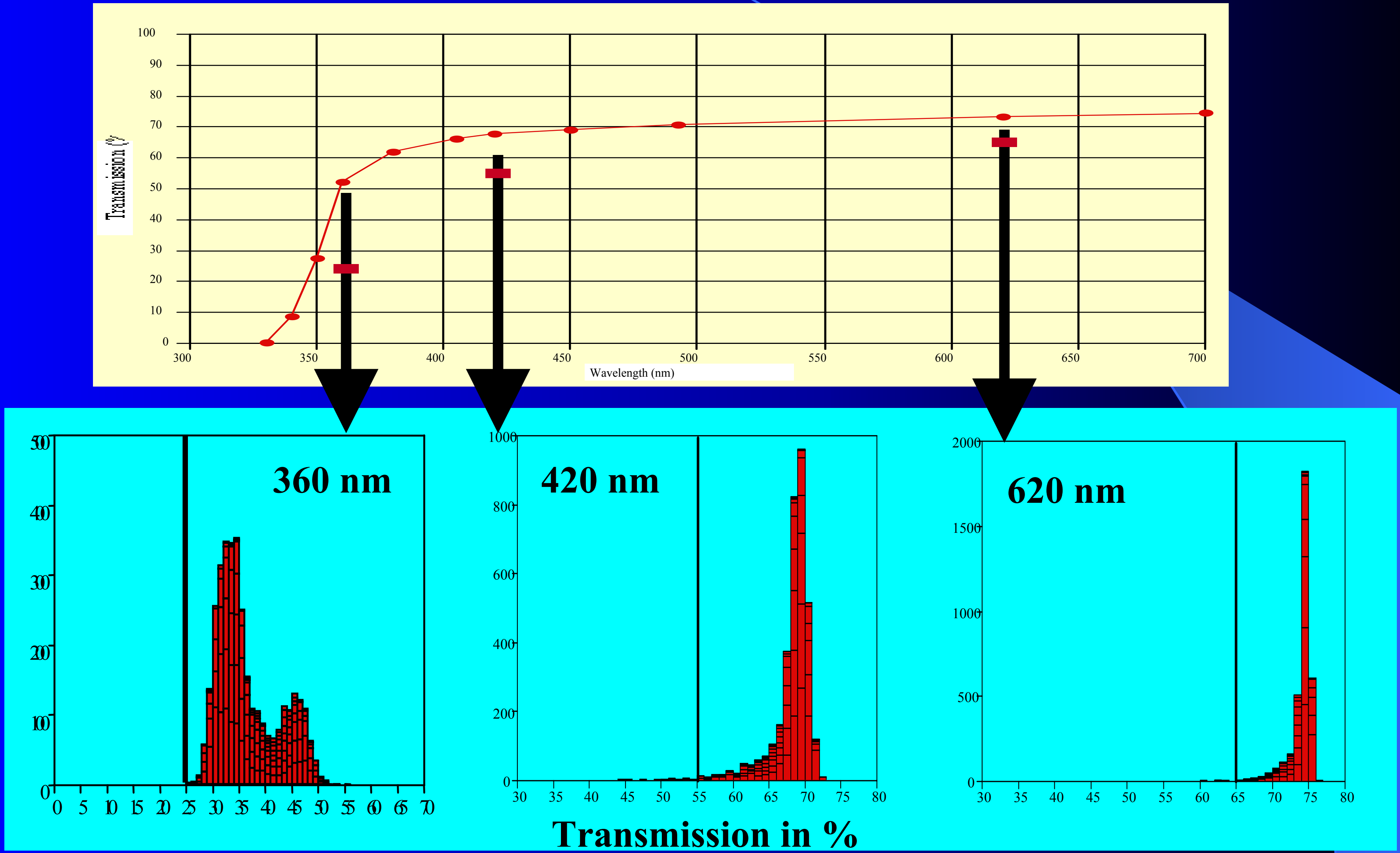
Dimensions:	General tolerance: +0.0 / -100 µm
Transmission:	T > 25% at 360 nm
	T > 55% at 420 nm
	T > 65% at 620 nm
Light Yield:	More than 8 photoelectrons per MeV at 18º C
Decay Time:	Light collected within 100 ns greater than 90% of light collected within 1000 ns
Slope/Radiation Hardness:	Slope of transmission curve between 340 nm and 370 nm larger than 3.0% per nm
	Induced absorption length: $0 < \mu < 1.5\ m^{-1}$ at 420 nm
	Light yield loss for front irrad. at 15 rad/hour: 0 < LYL < 6%

Correlation Transmission - Radiation

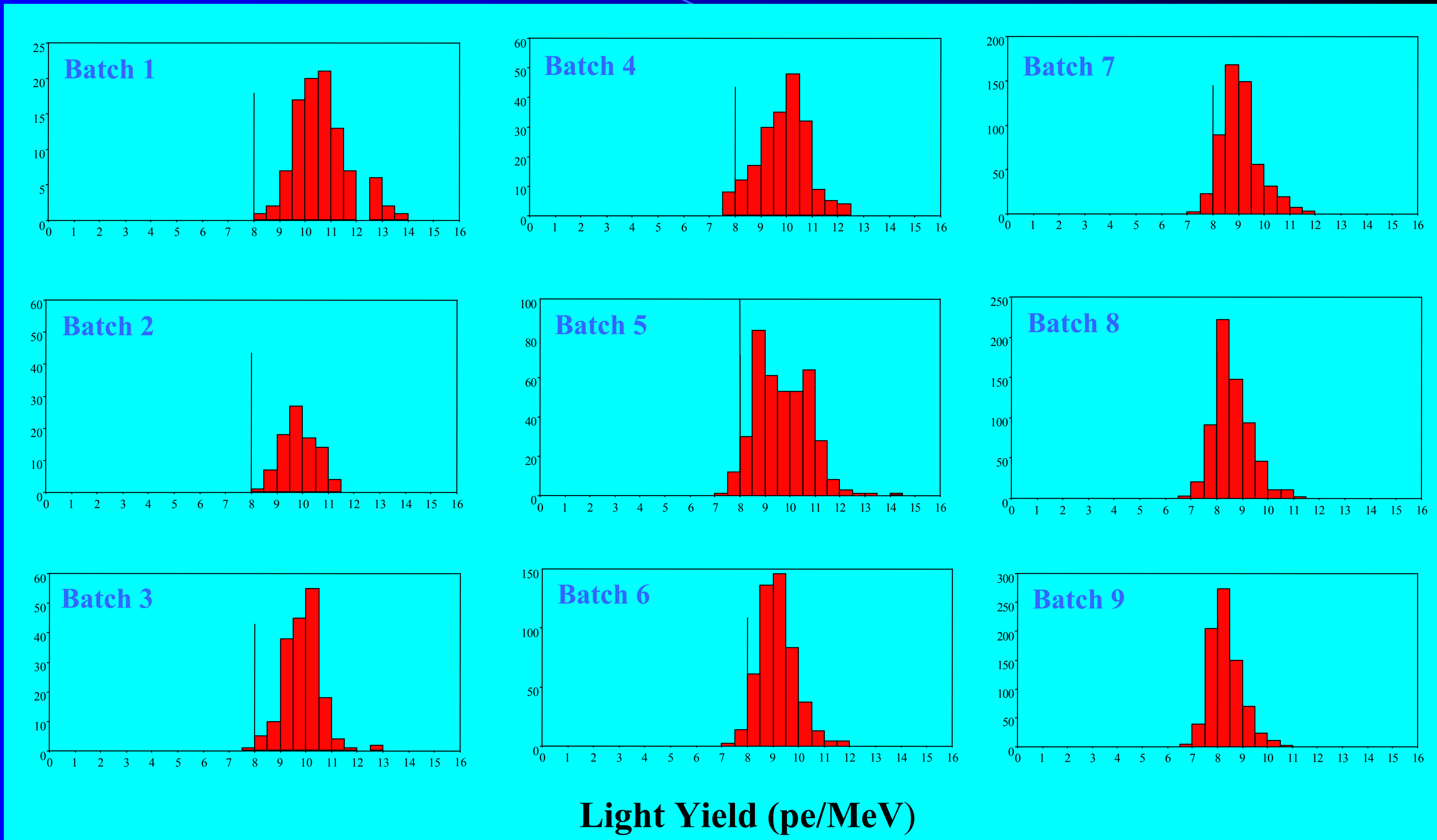


Crystal Acceptance: Transmission

Distributions for 3500 Crystals

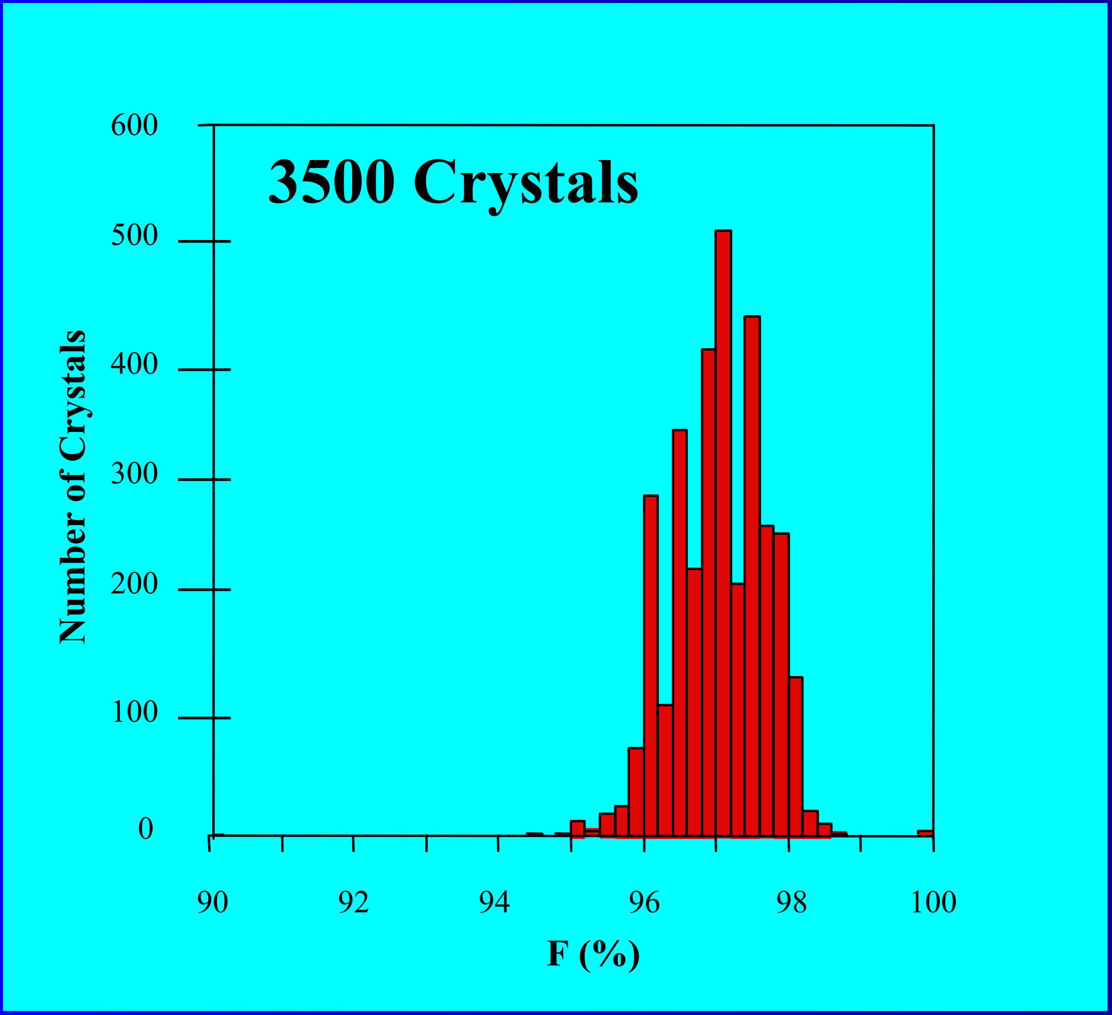


Crystal Acceptance: Light Yield



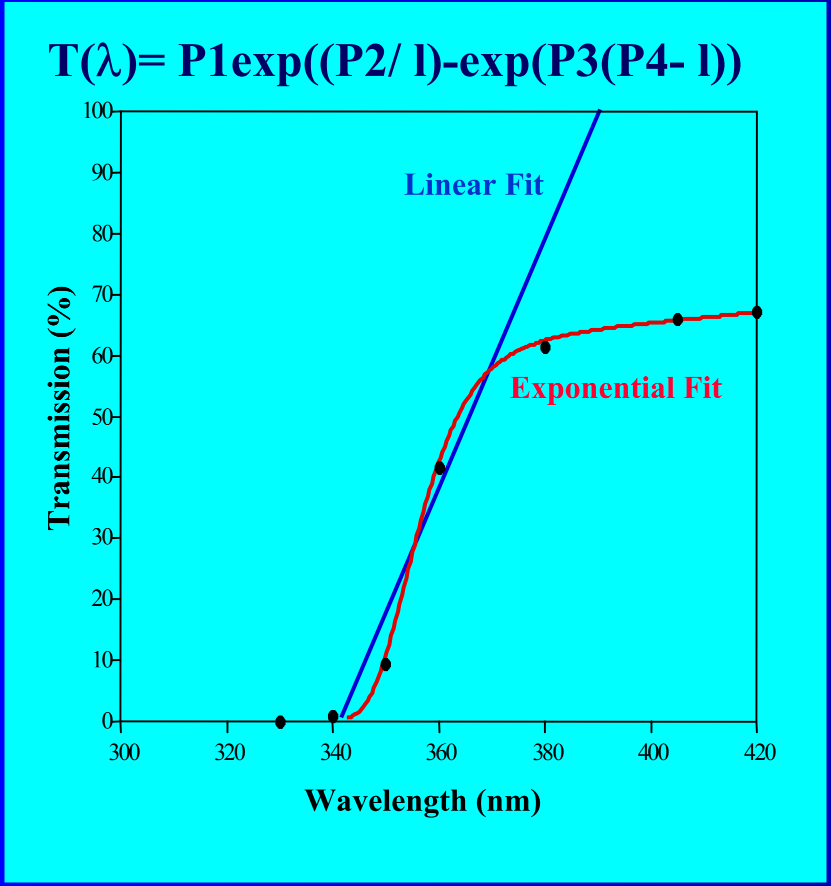
Crystal Acceptance: Decay Time

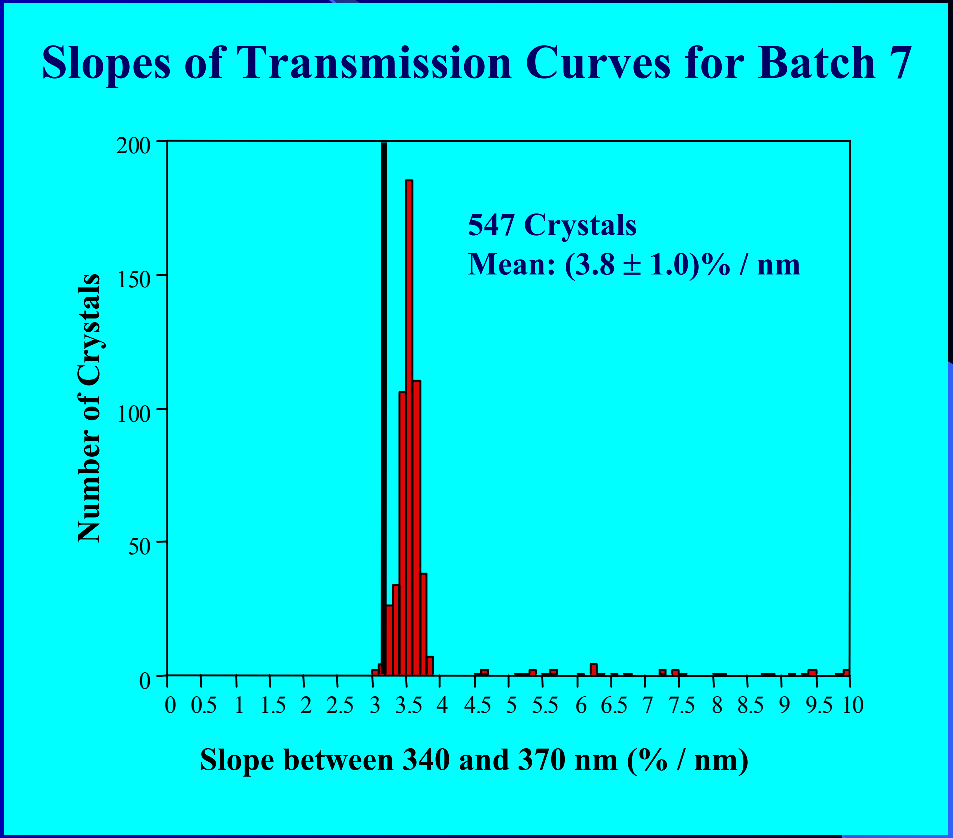
$$F = \frac{\text{Light Collected within 100ns}}{\text{Light Collected within 1000ns}}$$



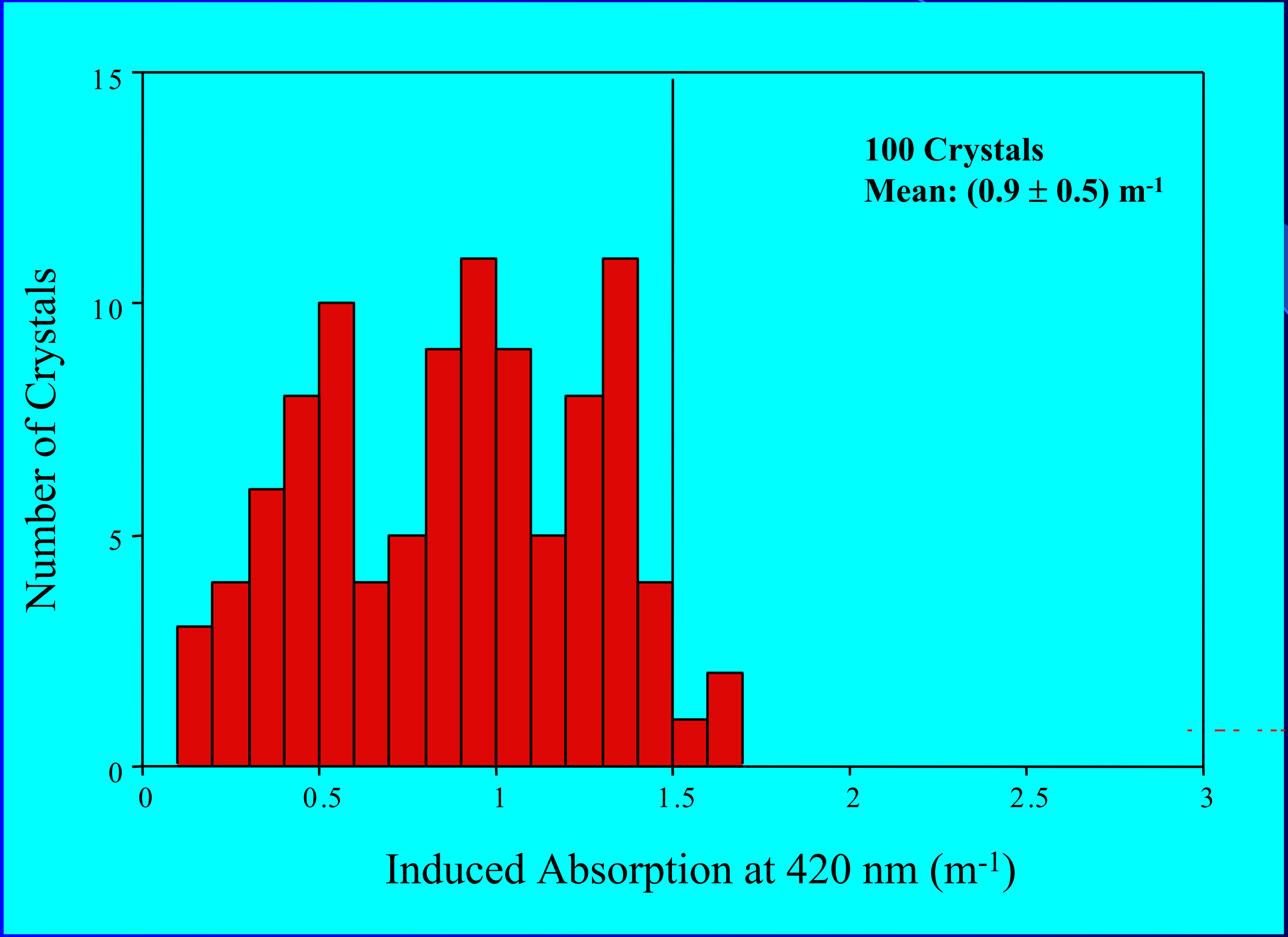
Specification: F > 90%

Crystal Acceptance: Slope of Transmission Curve





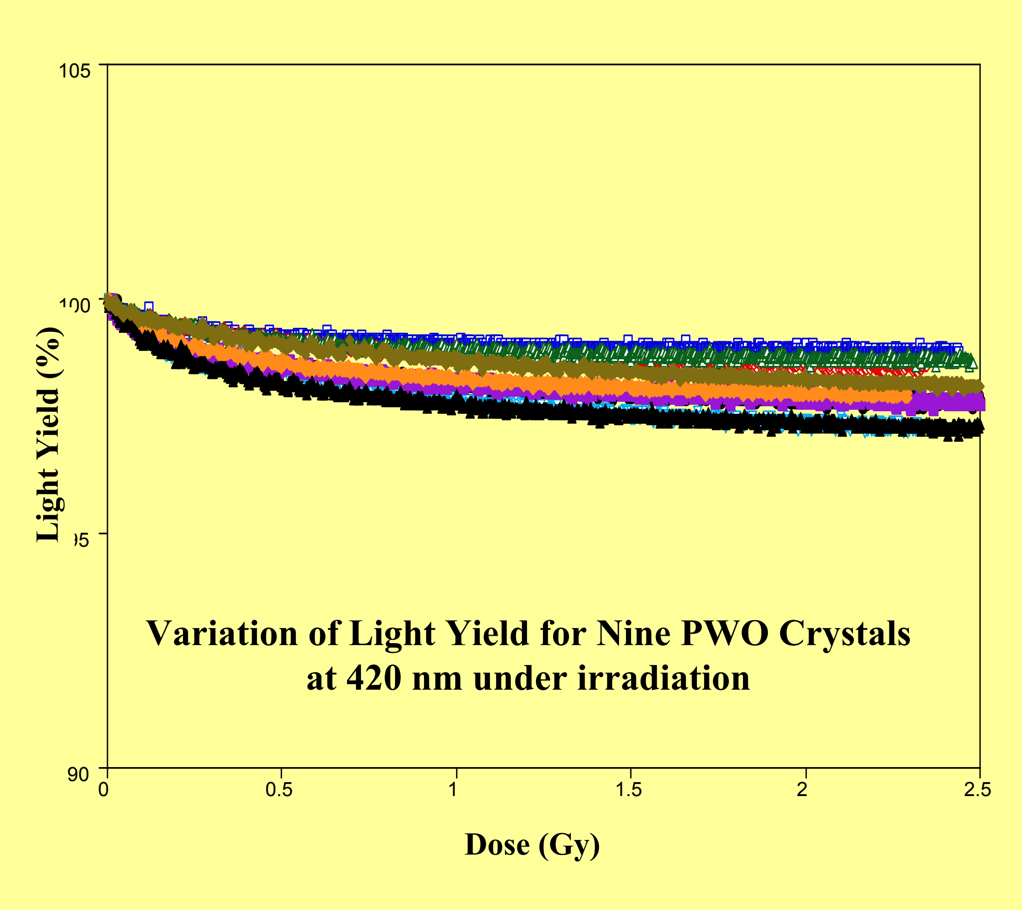
Crystal Acceptance: Induced Absorption

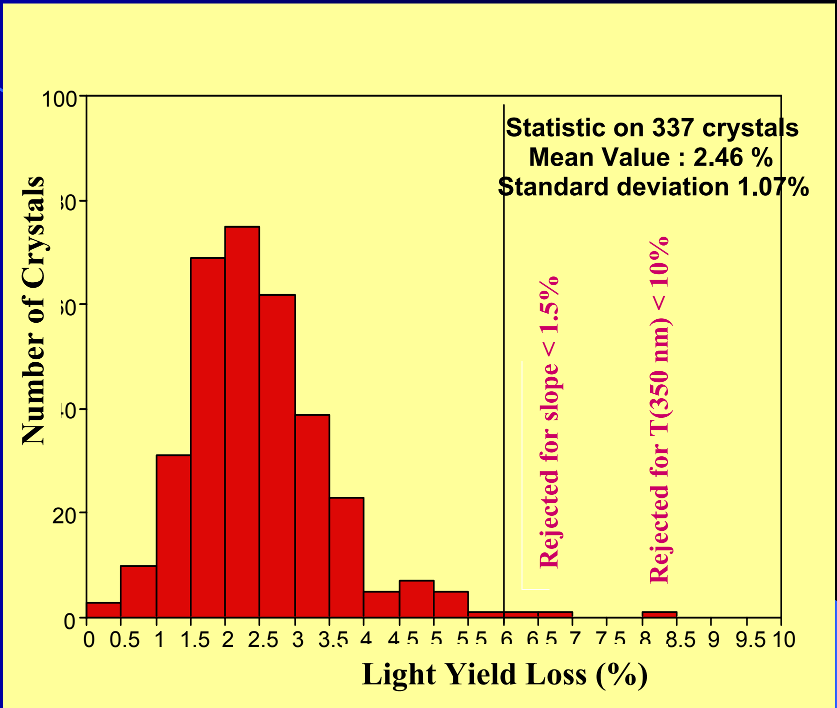


Lateral Irradiation
500Gy
240 Gy / h

Radiation Hardness – Light Yield Loss

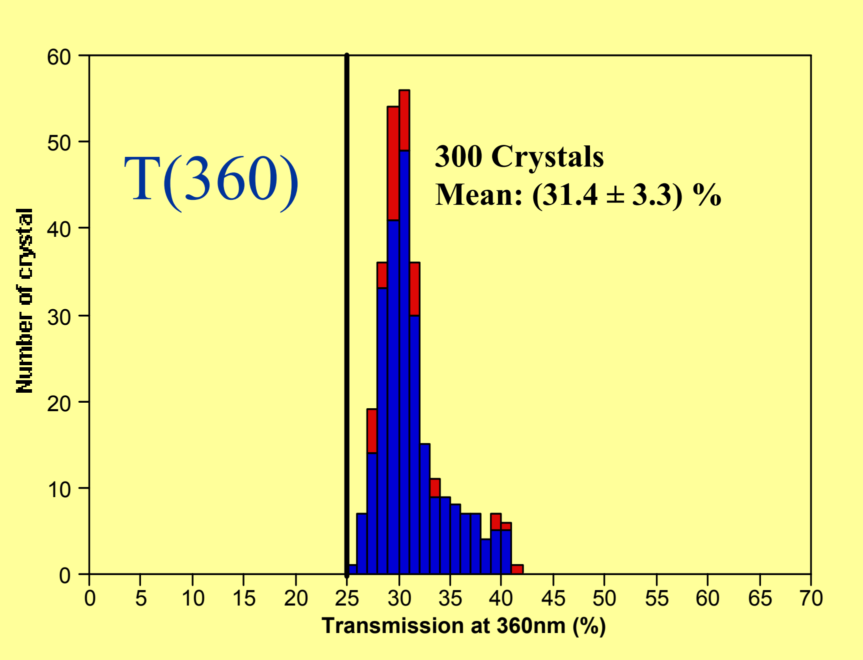
Front irradiation, 1.5 Gy, 0.15 Gy/h





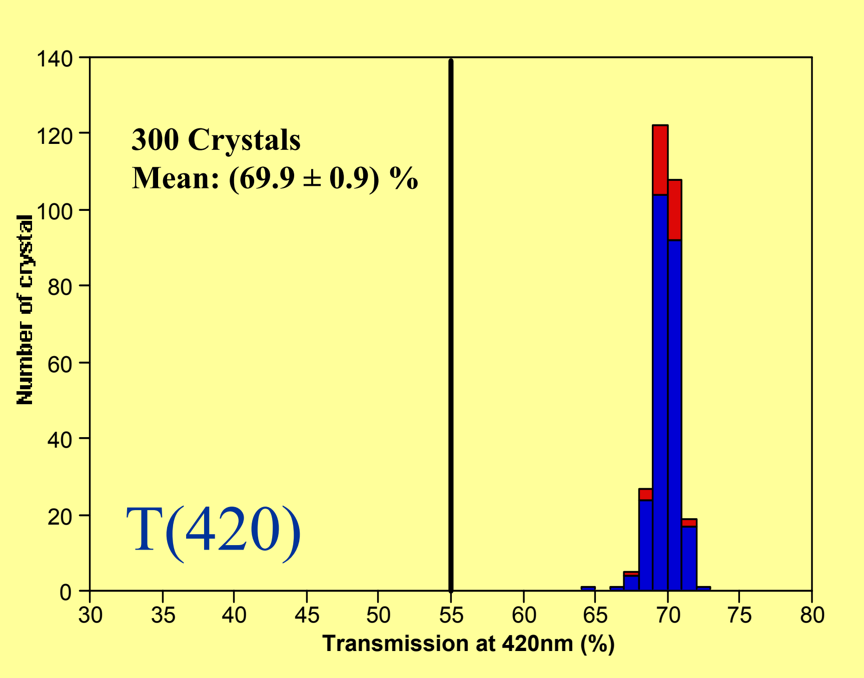
Radiation hardness improvements:
- stoichoimetric fine-tuning
- optimizing growth conditions
- doping (Y, Nb)
(last 2 also improved transmission)

Comparison New and Old Technology



Comparison:

- 260 barrel crystals produced with the standard technology
- 40 barrel crystals produced with the new technology



Crystal Deliveries from Bogoroditsk

- **Barrel: 14700 crystals delivered**
  - 6000 pre-production crystals (complete)
  - 8700 mass production crystals (total: 56000)

- **Endcaps:**
  - 100 crystals (initial mass production) ordered

Barrel crystals are not on the critical path.

Organization of ECAL Construction

Constructing the CMS Electromagnetic Calorimeter is a huge task.

Large quantities of different parts

Crystals – Photosensors – Electronics – Readout – Cooling - Mechanical Structures – Monitoring Systems – Integration - …

must be organized for about 78000 detector elements.

Not only is manufacture done by many suppliers all over the world, but also about 30 CMS institutes are involved in many aspects of the construction:

Design – Engineering – Prototyping – Procurement – Acceptance of Parts – Testing – Assembly – Installation - ...

Need professional quality control, modern communication, global organization, and industrial management.

Organization of ECAL Construction
Regional Centers

Work is distributed according to interest, experience, infrastructure and capacity among participating institutes.

Parts from different companies and laboratories are send to "CMS – ECAL Regional Centers" installed at CERN and ENEA (Italy).

All elements of the detector are measured and the recorded data is stored in a single database system accessible through the Web.

Final assembly of
modules into Supermodules (for the barrel) and supercrystals into Dees (for the endcaps)
is done at CERN before installation at the experimental area.

Activities at Regional Centers

Part Reception

Crystals, Capsules, Alveolar Structures, Tablets, Baskets, Capsules, etc.

Crystal Characterisation (ACCOS)

Measurements of the optical and mechanical properties conform to specifications

Capsule Gluing

Crystals + Capsules = Subunit

Submodule Assembly

1 Submodule = 10 Subunits

Module Assembly

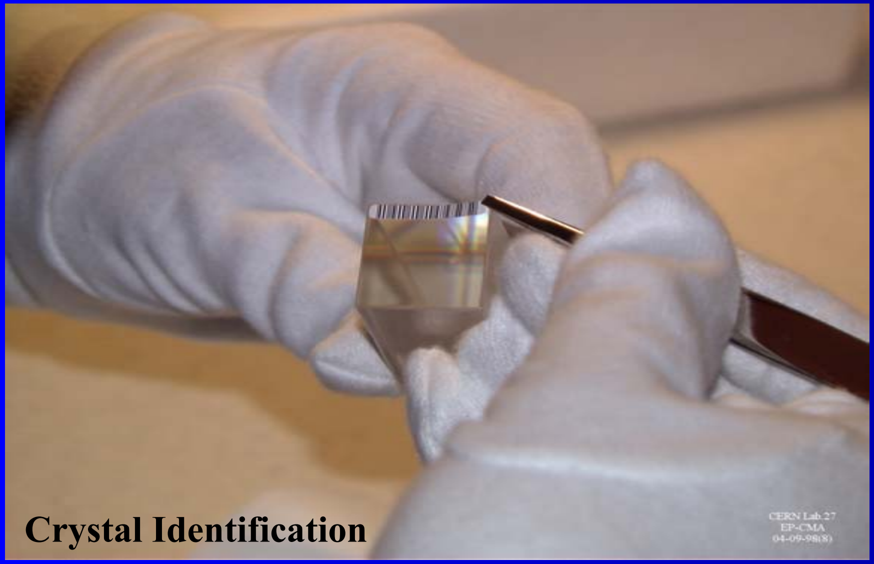
50 Submodules for type 1

40 Submodules for types 2, 3, and 4

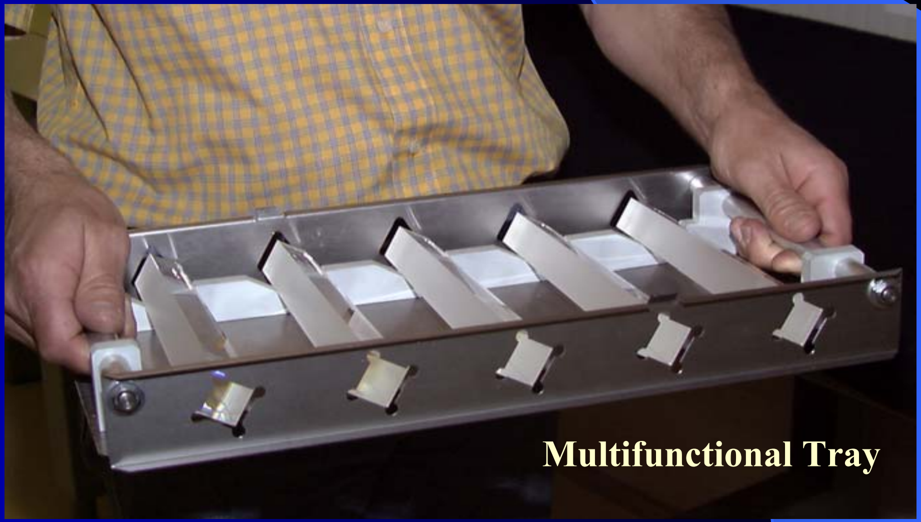
Crystal Reception and Registration at CERN

Arrival at CERN

Crystal Registration & Visual Inspection



Crystal Identification


Multifunctional Tray

Crystal Acceptance with ACCOS
Automatic Crystal Control System

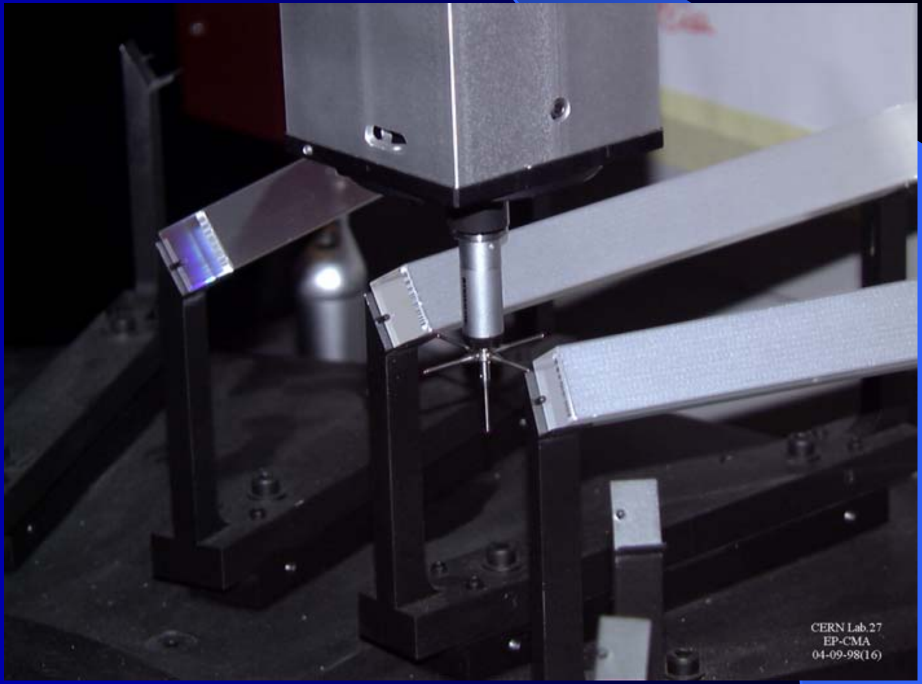
- Measure dimensions, transmissions and light yield
- Equivalent instruments at the crystal production centre and the Regional Centers
- All data stored in single, common database

Crystal Acceptance with ACCOS

Identification and Dimension Measurements

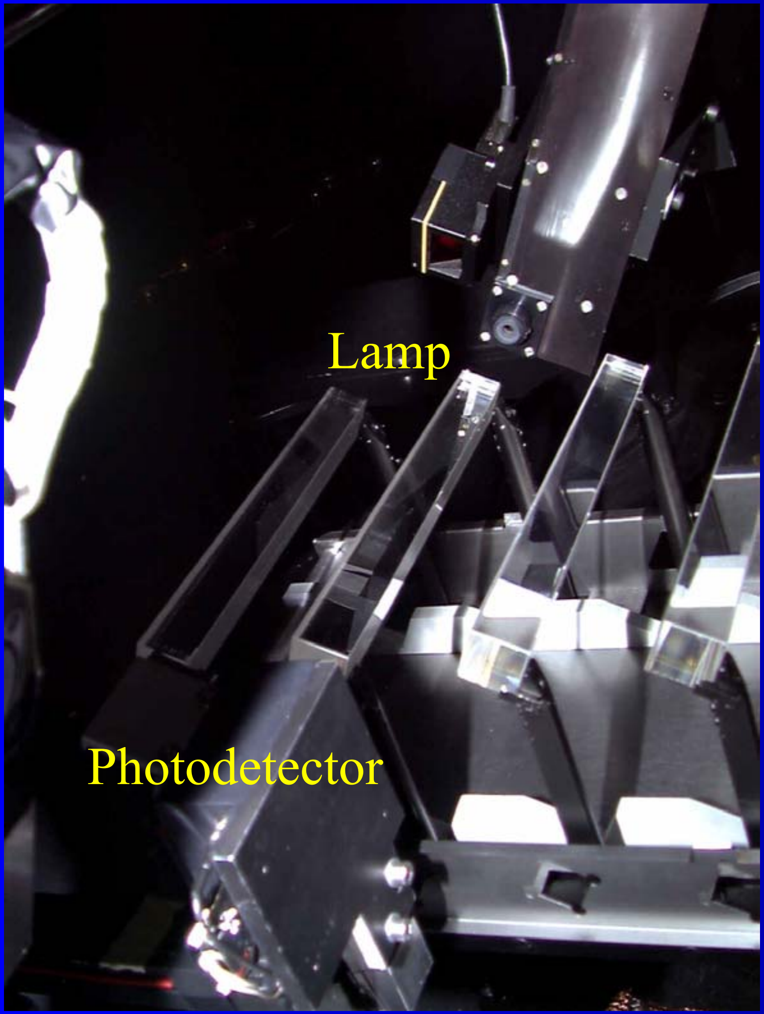
Barcode Reading

Dimension Measurements

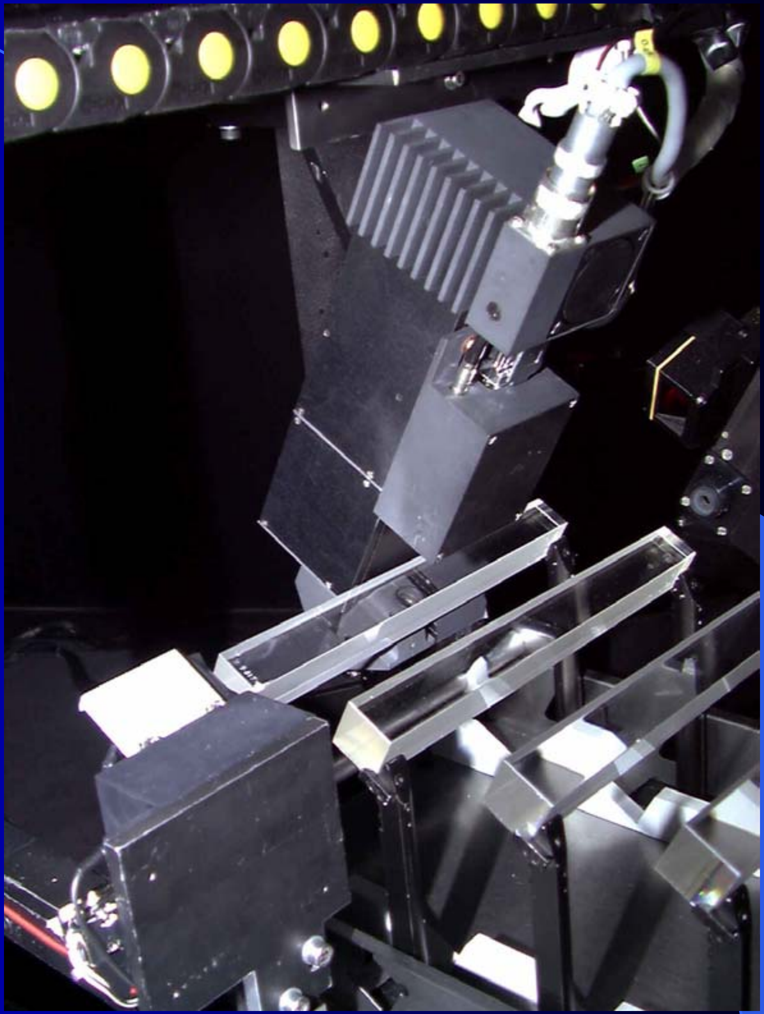


Crystal Acceptance with ACCOS

Measurements of Optical Properties



Longitudinal Transmission



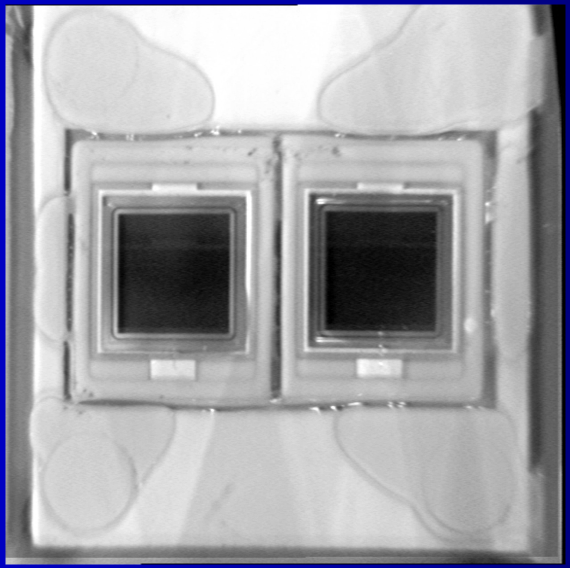
Transversal Transmission

Avalanche Photodiodes Glued to Capsules

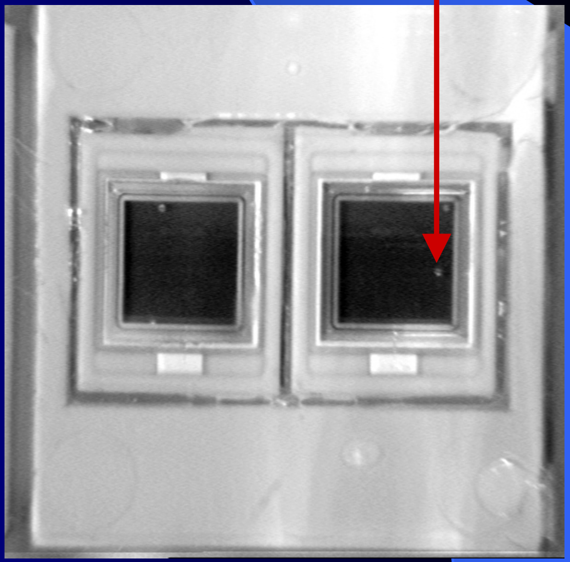
Capsule size: 20 × 20 mm^2

Quality Control sorts out capsules with bubbles

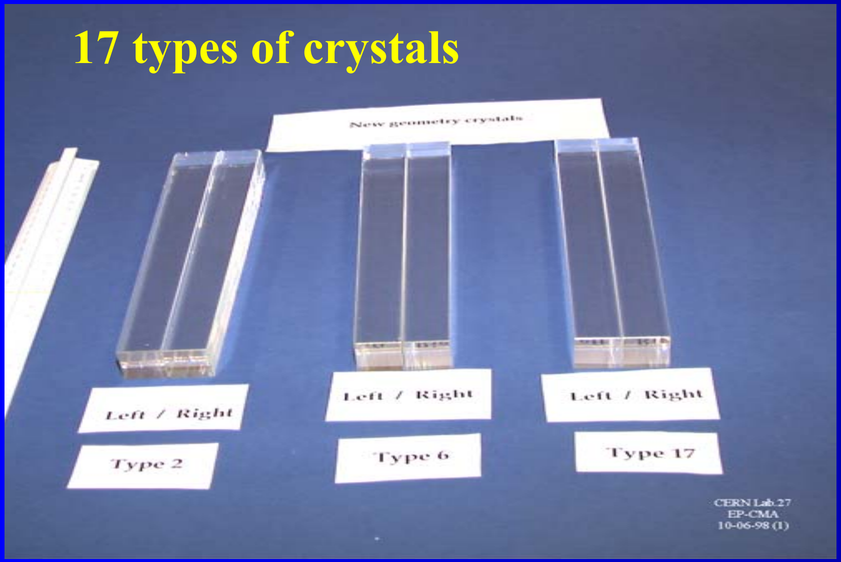
No Bubbles

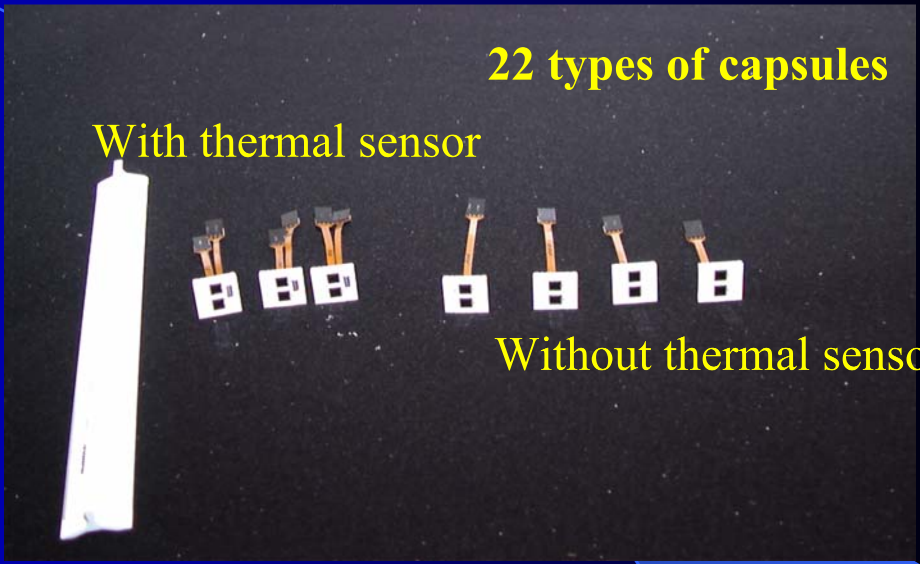


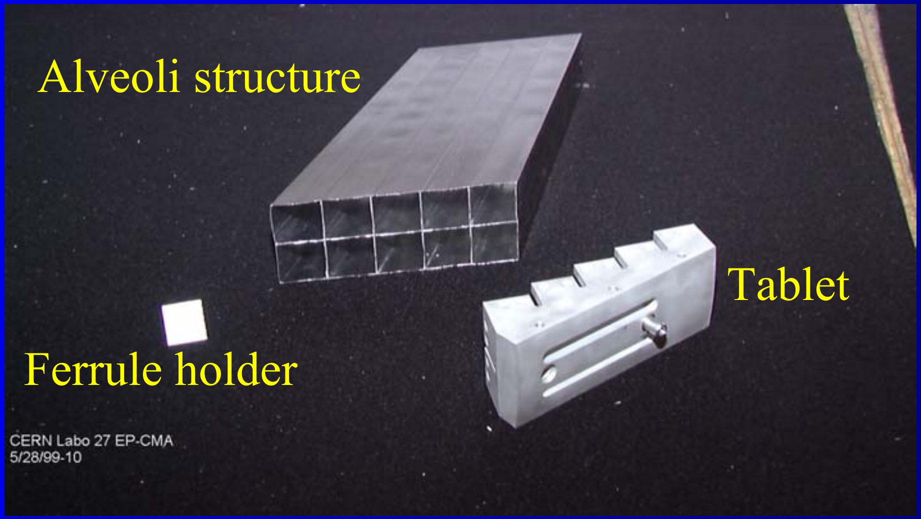
Bubbles



Submodule Elements

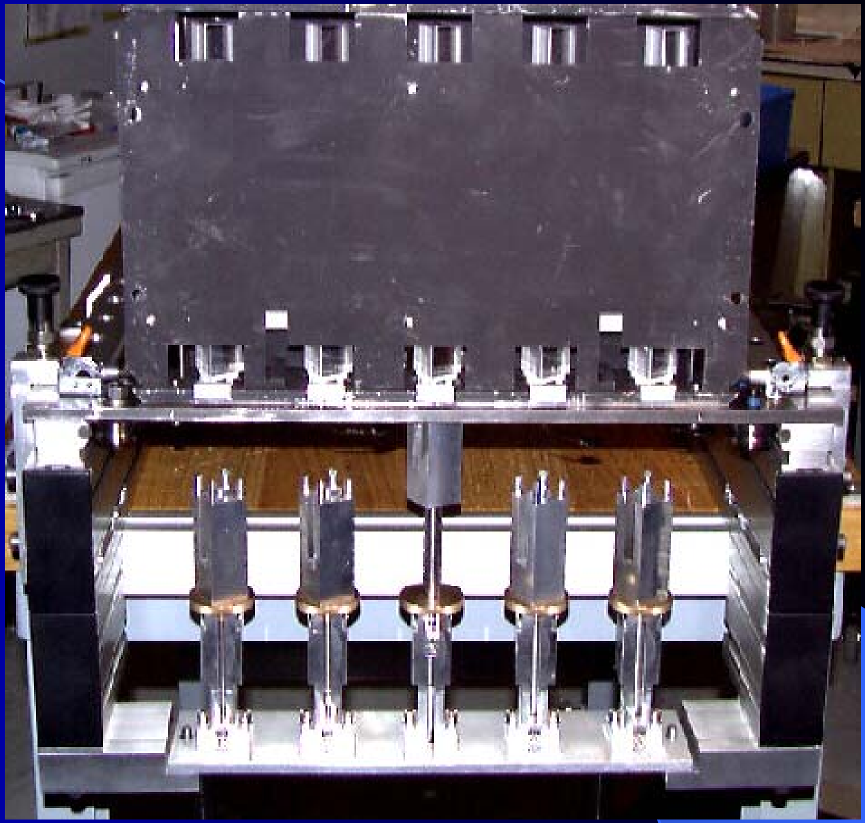






Gluing Capsules onto Crystals

APDs are glued on plastic holders "capsules".
Some capsules also have a thermal sensor.
This work is done in Lyon.

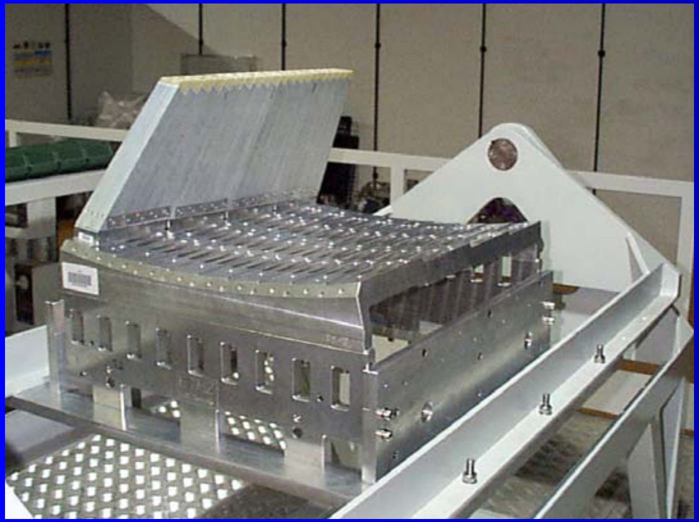


Capsules are glued to the rear face of crystals.
Subunits are complete.

Assembly of “Subunits” into “Submodules”

Ten Subunits are inserted into the alveolar structure containing 5 × 2 cells.
This is then the Submodule.

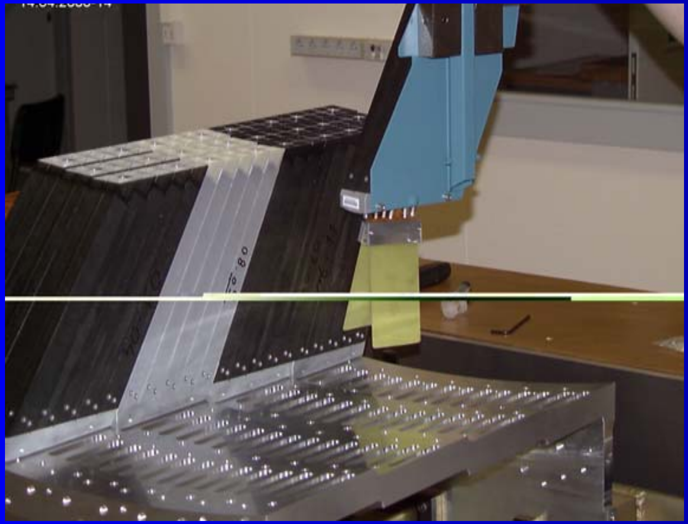
Submodules become Modules



Start of Module assembly

There are four different types of Modules.

Type 1 contains 50 submodules (500 crystals),
types 2, 3 and 4 contain 40 submodules (3×400 crystals).

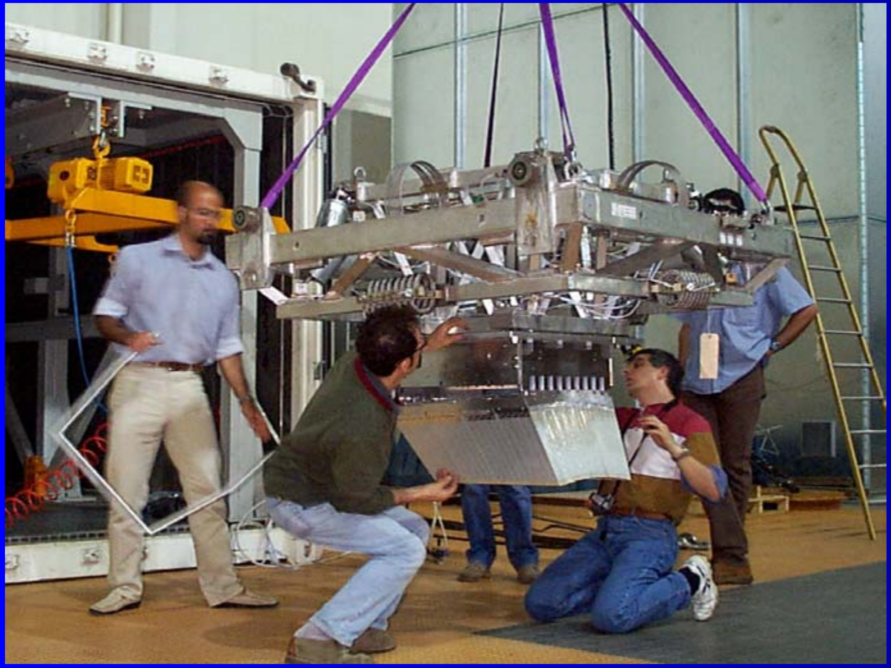


Loading of a Submodule

Completed Module

… finally Modules are Assembled into Supermodules

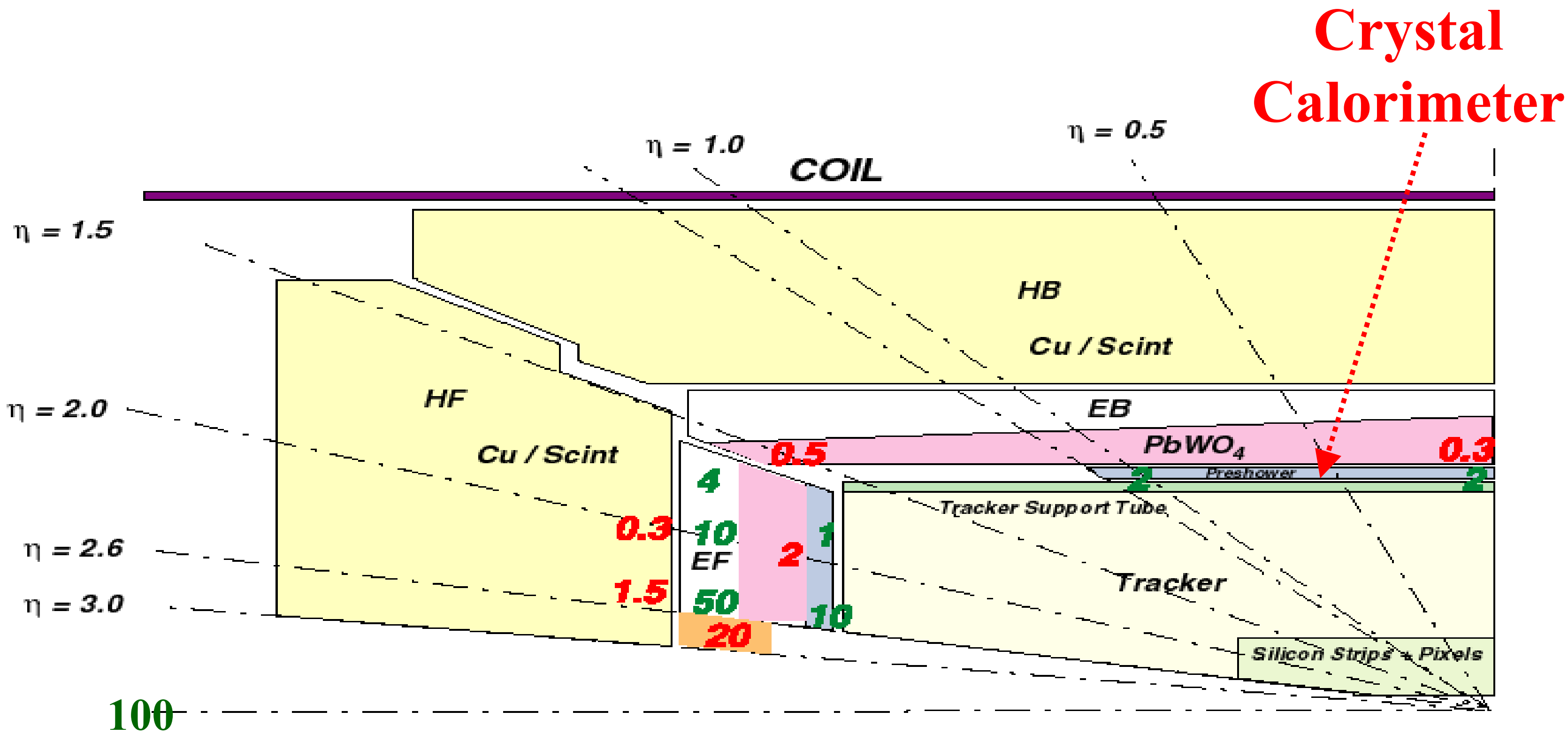
Modules of type 2 and 3 assembled at ENEA were shipped to CERN.



The first of 36 Supermodules was completed in July 2002.

High Precision Radiation Hard Photosensor

Selection of Photodetector for CMS – Radiation Hardness



Radiation doses are in red, 10^4 Gy.

Neutron fluence in green 10^{13} neutrons/cm ^{2} with E > 100 keV.

High Precision Radiation Hard Photosensor

Comparison Photomultiplier vs. Avalanche Photodiode

The main disadvantage of APDs is the moderate gain in the range of 100 to 10.000.

A charge sensitive amplifier is required which adds to the cost and which destroys the very fast rise time (2 ns) of the APD.

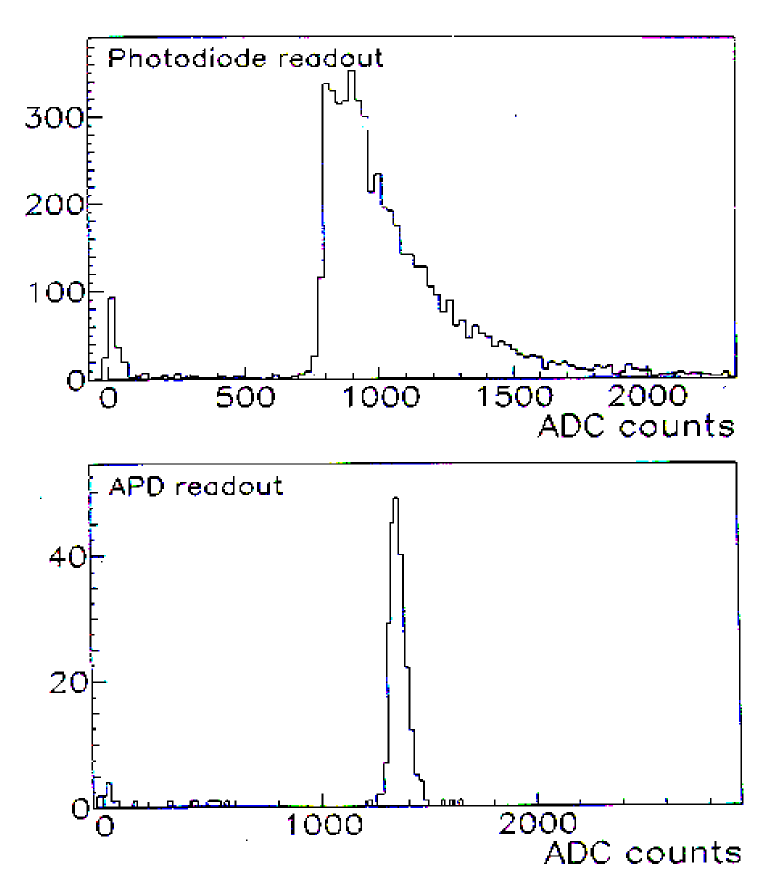
	PM	APD
Price	high	low
Active area	big	small
Shape	bulky	small
Weight	high	low
Gain	very high	moderate
Quantum efficiency	~ 25 %	~ 80 %
Speed	very fast	fast
Ruggedness	moderate	high
Power requirement	high	low
Sensitivity to temperature	low	moderate
Sensitivity to voltage changes	moderate	moderate
Sensitivity to magnetic fields	high	no

High Precision Radiation Hard Photosensor

Selection of Avalanche Photodiodes for CMS - Precision

Historical (1992) comparison of the response to 80 GeV electrons recorded with a lead tungstate crystal with a PIN diode (top) and an APD (bottom) read-out.

The tail to the right of the peak in the PIN diode spectrum is due to particles leaking out of the back of the 18 cm long crystal and passing through the diode (nuclear counter effect).



Early 1990es:	**Push for a homogeneous calorimeter**
Late 1992:	**First APD prototype from Hamamatsu**
1995:	**Test of an APD on a $PbWO_4$ crystal in a CERN test beam**
1996-97:	**APDs chosen for CMS - ECAL**

High Precision Radiation Hard Photosensor

Selection of Avalanche Photodiodes for CMS – Energy Resolution

ECAL energy resolution: $$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

CMS design goal (barrel)

***a* ~ 3 %, *b* ~ 0.55 %, *c* ~ 150 MeV**

Photodetectors contribute to:

a: photo statistics (area, QE) and avalanche fluctuations (excess noise factor)

b: stability (gain, sensitivity to voltage, temperature variation, aging and radiation damage)

c: noise (low capacitance, serial resistance and dark current)

High Precision Radiation Hard Photosensor

Selection of Avalanche Photodiodes for CMS – Requirements

Fulfilling ECAL energy resolution requirements

Insensitivity to particles traversing the diode

Radiation hard ($2 \cdot 10^{13}$ n/cm^2 + 250 kRad)

Operate in 4 Tesla field

Fast ($\leq$ 10 ns)

Affordable (61200 crystals)

These requirements triggered an eight year R&D effort in collaboration with Hamamatsu (and initially EG&G).

Avalanche Photodiodes for CMS
Characteristics

Active area (2 APDs per crystal)	5 x 5 mm^2 (each)	
Quantum efficiency (at 430 nm)	75%	
Light collection within 20 ns	$(99 \pm 1)\%$	
Operating voltage	340 V – 440 V	
Gain (M)	50	(Max >1000)
Distance Breakdown to Operating Voltage	> 40 V	
Capacitance	80 pF	
Serial resistance	3 Ω	
Dark current	< 50 nA	(~ 10 nA typical)
Voltage sensitivity (1/M*dM/dV)	3.15% / V	
Temperature sensitivity (1/T*dM/dT)	- 2.2% / V	
Thickness sensitive to ionizing particles	5 µm	

After radiation and accelerated aging equivalent to 10 years of LHC, ONLY quantity to change is the dark current, which rises to 5 µA

Avalanche Photodiodes for CMS

Basic Structure

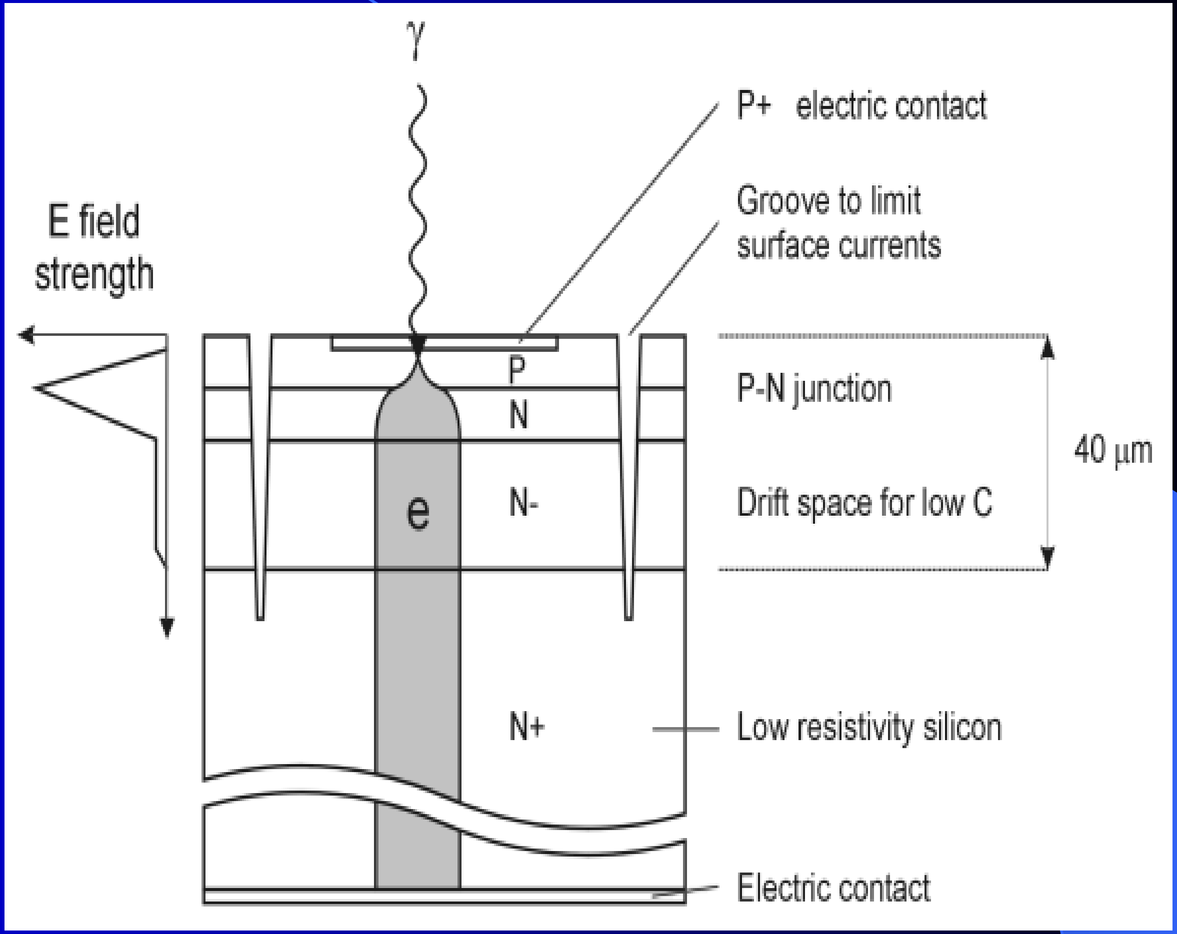
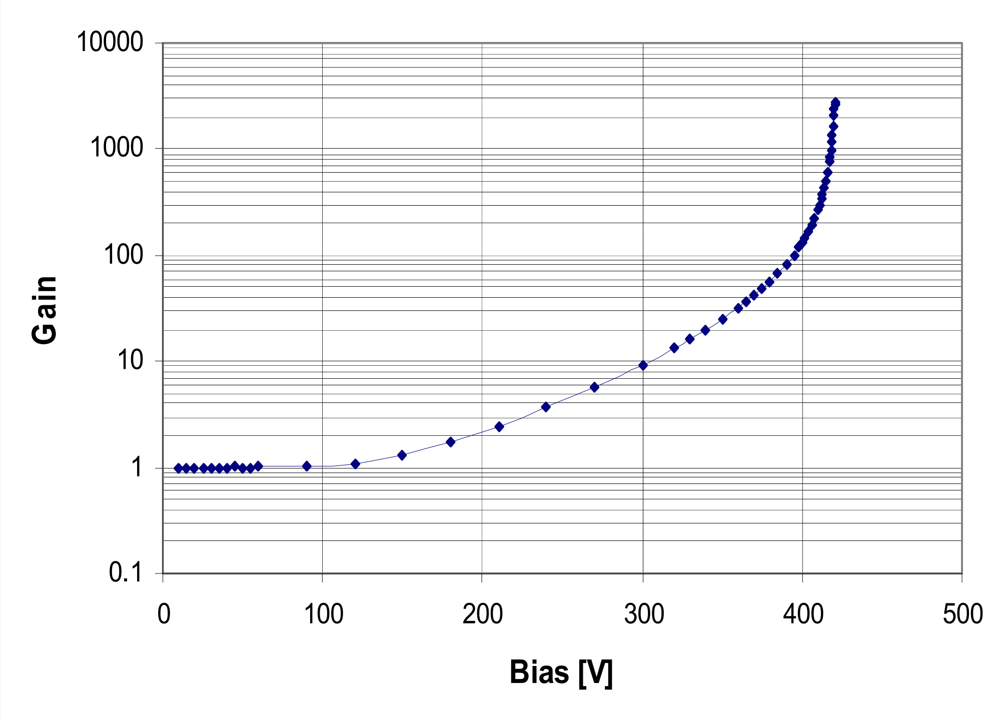
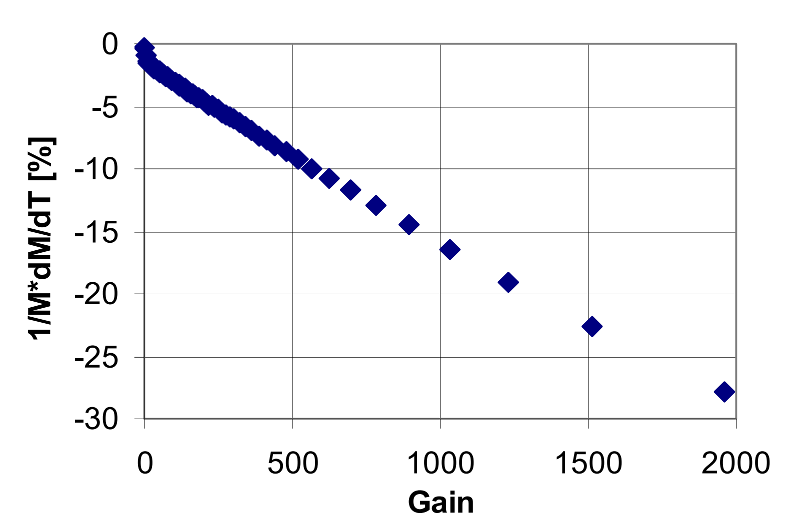


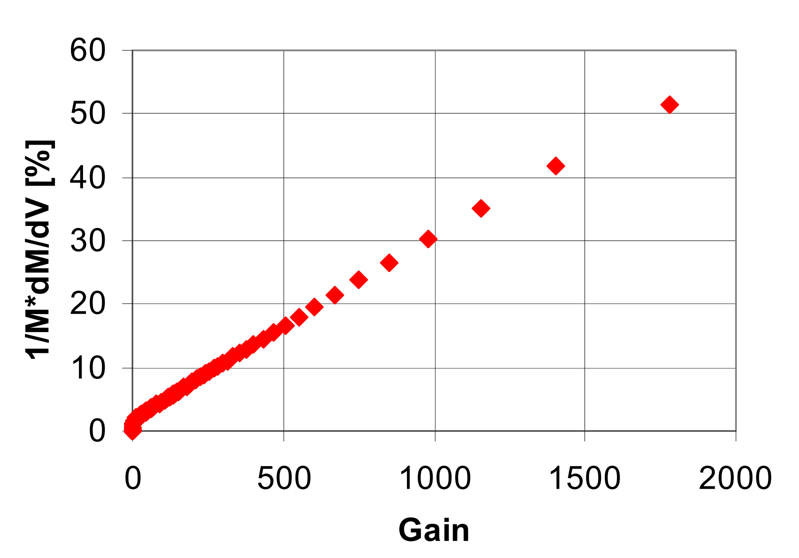
Photo-conversion electrons from the thin p-layer induce avalanche amplification at the p-n junction.

Electrons from ionising particles traversing the bulk are not amplified.

Avalanche Photodiodes for CMS
Gain, V and T Sensitivity



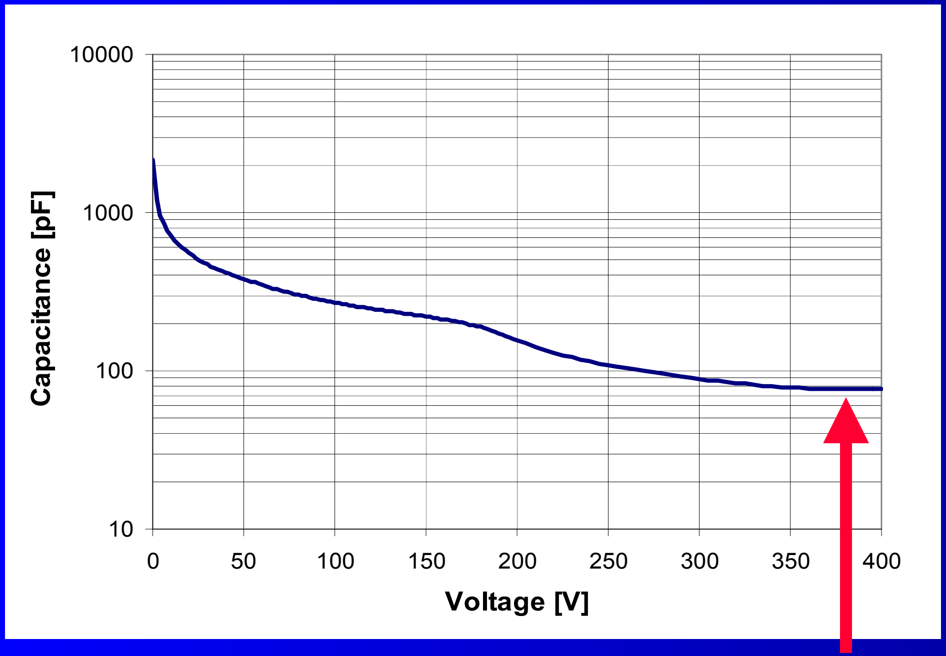


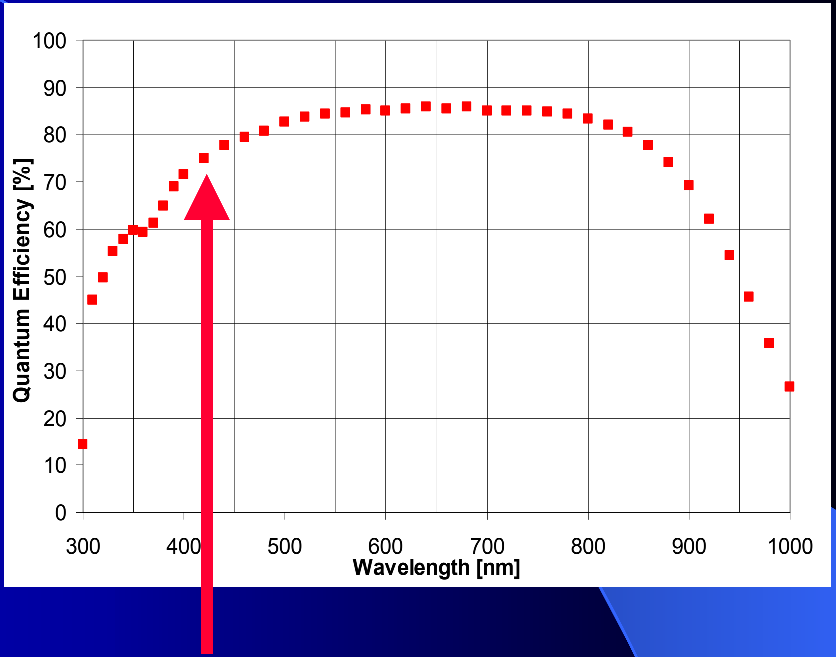


Required stability to achieve energy resolution is 40 mV.
Prototypes made by CAEN (Italy) and ISEG (Germany)
fulfilled this requirement after about two years.
HV system under manufacture by CAEN.

Avalanche Photodiodes for CMS

Capacitance and Quantum Efficiency





Operating Voltage V_r

PWO peak emission

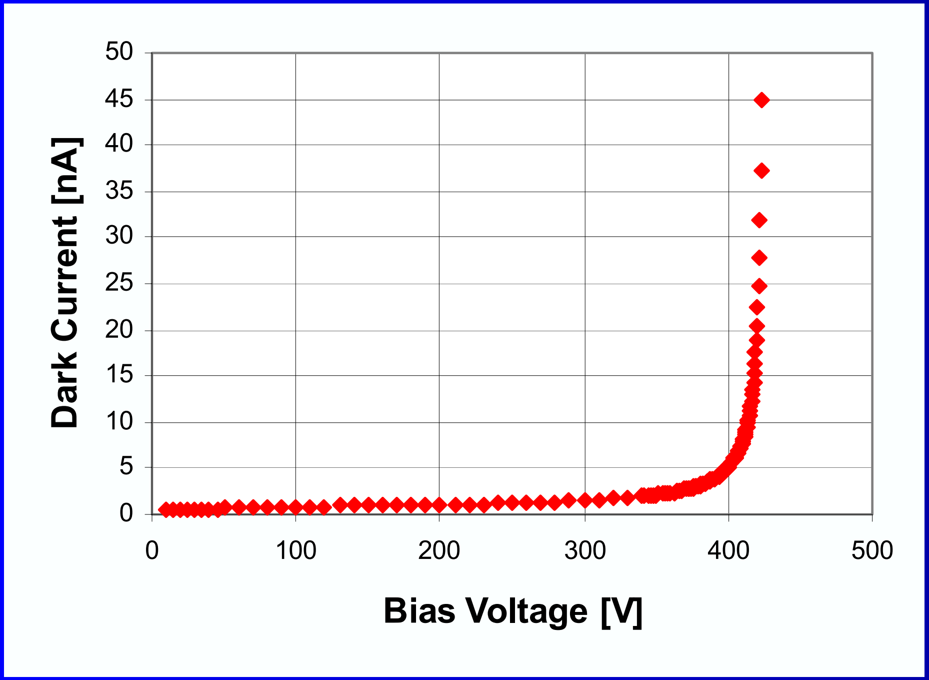
APD is fully depleted at operating voltage

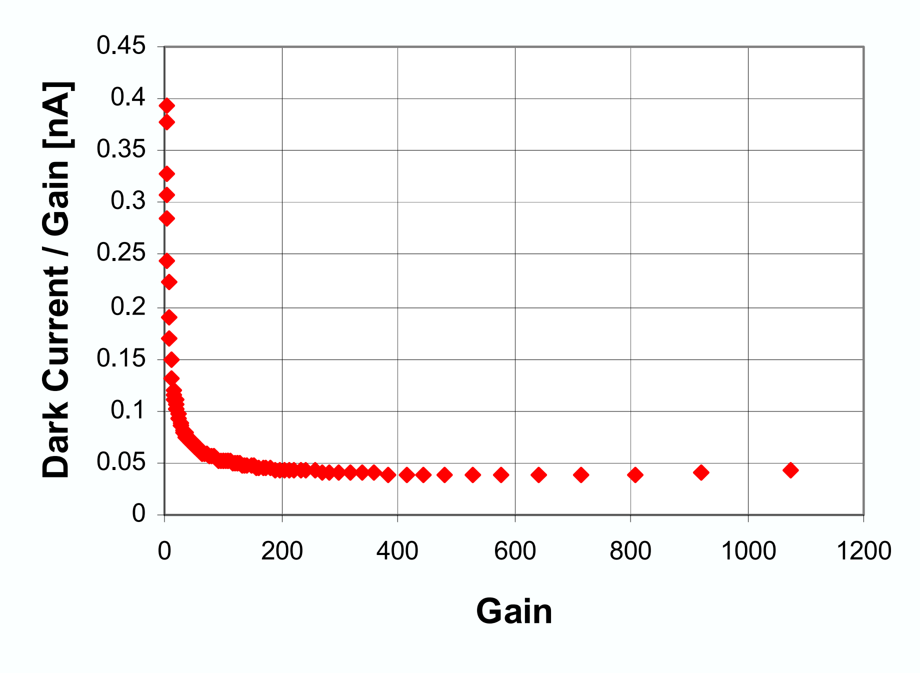
Quantum efficiency is 75% at peak emission

No change in quantum efficiency after irradiation with 10^{13} p/cm^2

Avalanche Photodiodes for CMS

Dark Current

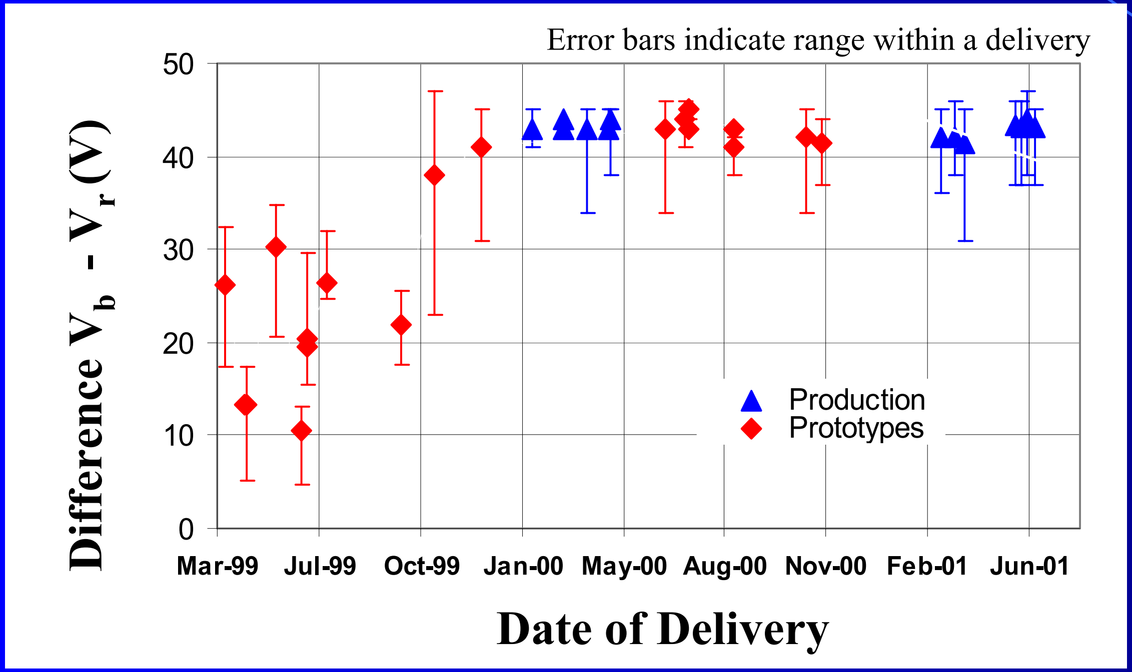




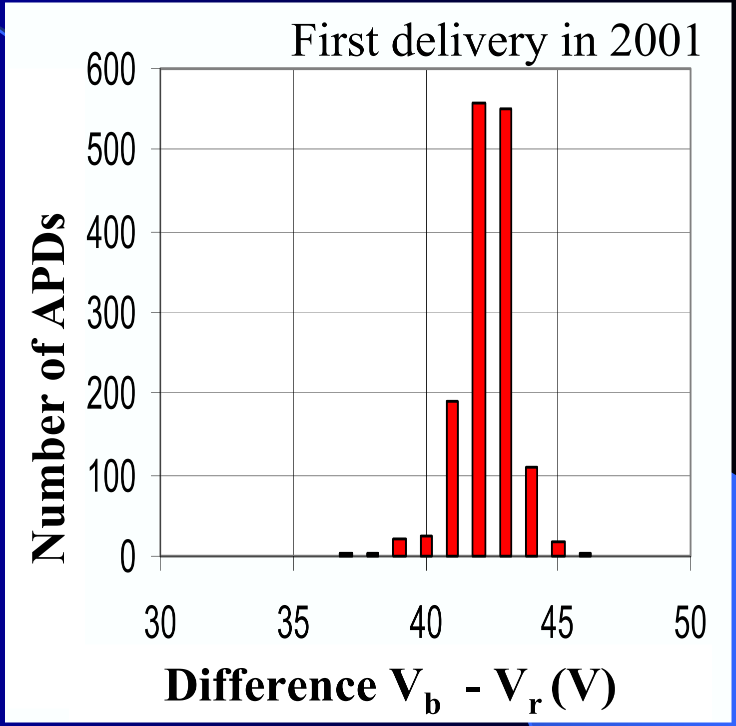
Improving APD Performance

Difference Between Breakdown V_b and Operating Voltage V_r

Difference should be large



Spread in V_b - V_r is small



Side remark: Thousands of APDs have been tested and sometimes "accidents" happened.
APDs were biased with the wrong polarity for a long period or the bias voltage was far too high (3000 V instead of 300 V).
No APD ever died due to such an event.

V_b - V_r found important indicator of radiation hardness

APD Acceptance: Radiation Tests

Production in 2000

At beginning of production few percent of delivered APDs "died"
(i.e. breakdown voltage drops below operating voltage)
1. in accelerated aging testing (80º C - 90º C)
2. in radiation testing (protons)

==> Production stopped

Case 1: Origin soon traced by Hamamatsu. Problem was solved.

Case 2: Proved much harder.
Complex with number of different causes:
- over 6 months intensive R&D by Hamamatsu
- review of radiation testing procedures at PSI

==> Production restarted (March, 2001)

APD Acceptance: Radiation Tests

Conclusions of R&D by Hamamatsu:

Basic APD structure is radiation hard and shall not be changed.

Solution: modify geometry to reduce lateral fields
(rounder corners, change spacings between structures, field clamps, etc.)

Detailed Study of APDs:

"Bad" APDs found sensitive to Co γ-irradiation, not sensitive to neutrons:
i.e problem at surface, not inside the silicon.

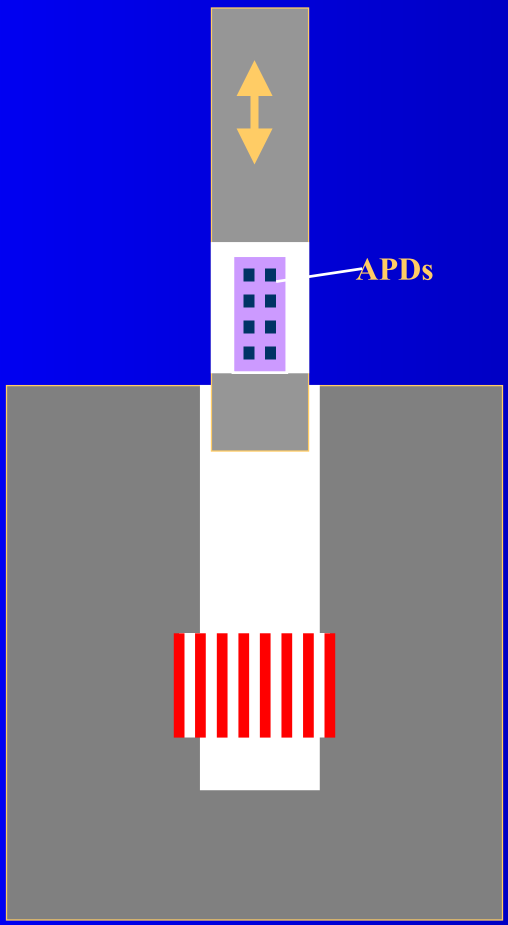
Introduce new three stage irradiation test procedure:

1. Screening of all APDs with Co γ-irradiation (500 kRad)
- reject on lowered breakdown voltage V_b, anomalous dark current, abnormal high noise.

2. followed by 2 weeks annealing/aging testing at 90 º C

3. sampling (5%) testing with 2×10^{13} neutrons/cm^2

^{60}Co Irradiation at PSI



APDs come from Hamamatsu mounted on special boards, designed at PSI (80 APDs/board).
They are irradiated, annealed and measured remaining on the boards.
APDs are removed from the boards during sorting.

All APDs are irradiated with ^{60}Co γ-source

Isotropic source: 32 wires containing ^{60}Co

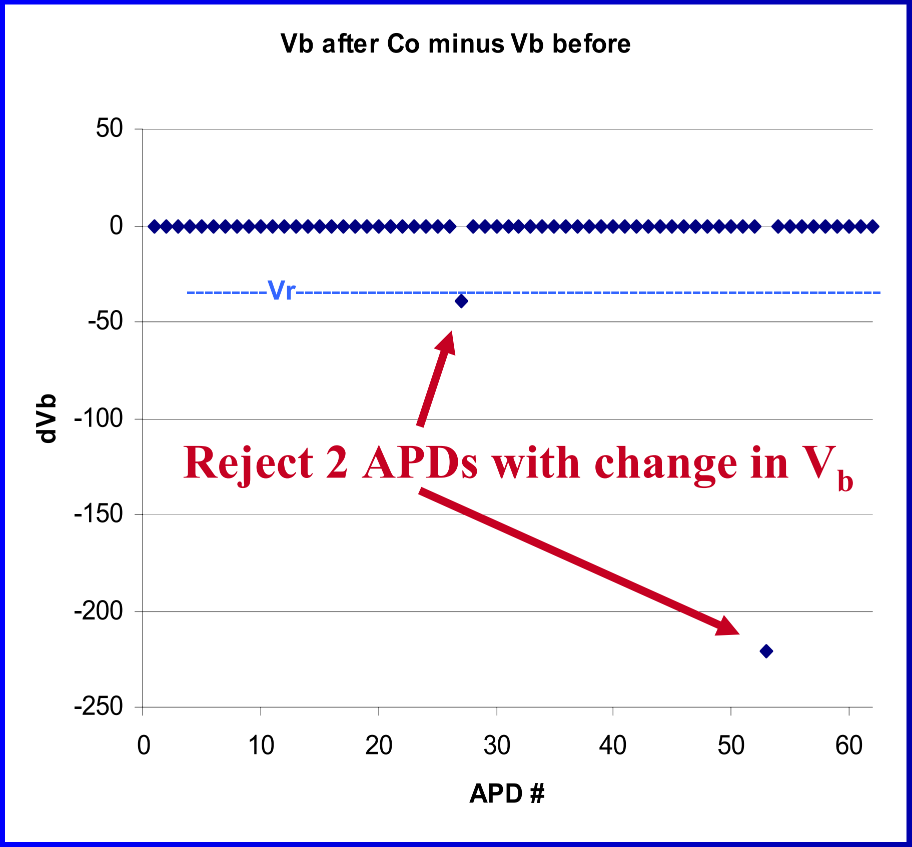
5 kGy in 2 hours

5 - 6 boards/day (400 - 480 APDs/day)

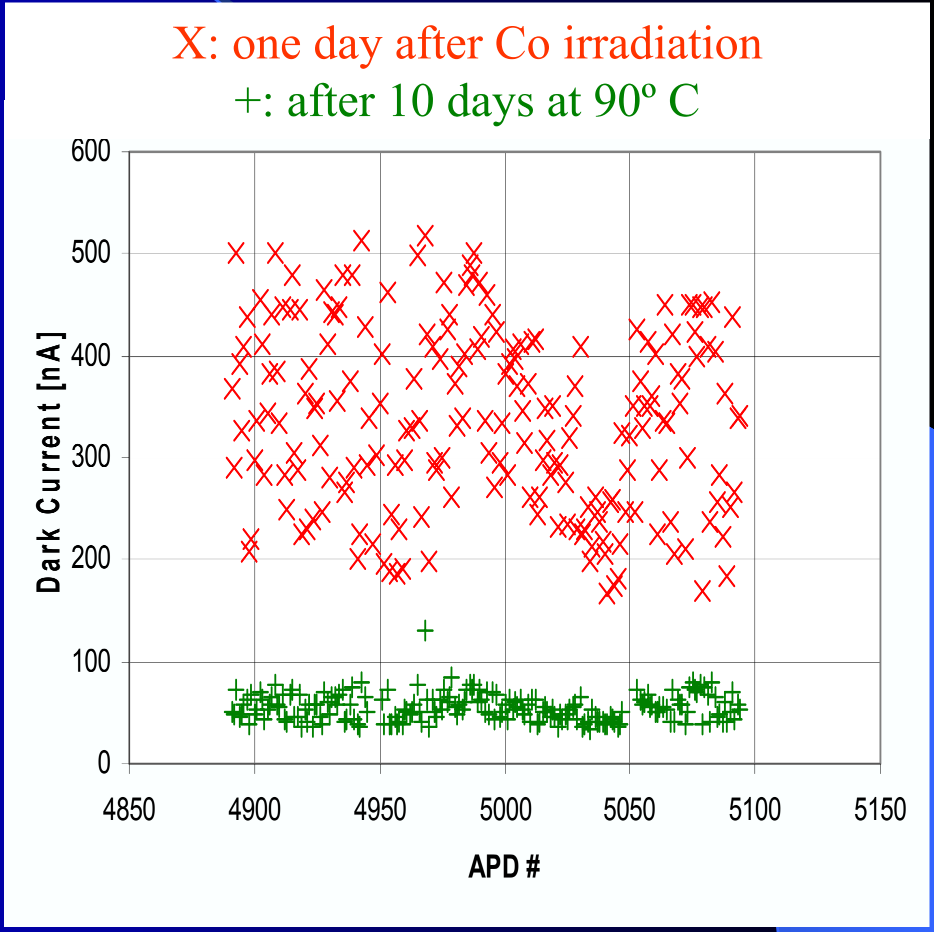
Source is available 4 days/week

Cobalt Screening Results

Change in V_b after Co irradiation



Induced dark current almost completely anneals after ten days at 90º C



APD Quality and Status of Delivery

The Hamamatsu APD meets all the specifications.

Radiation hardness proved hardest to achieve. Now satisfactory.
With new screening procedure all APDs will be irradiated.
Expect to achieve acceptance rate >> 99%.

Mass production at full rate (> 1000/week).

About 56,000 (of 130,000) APDs accepted.

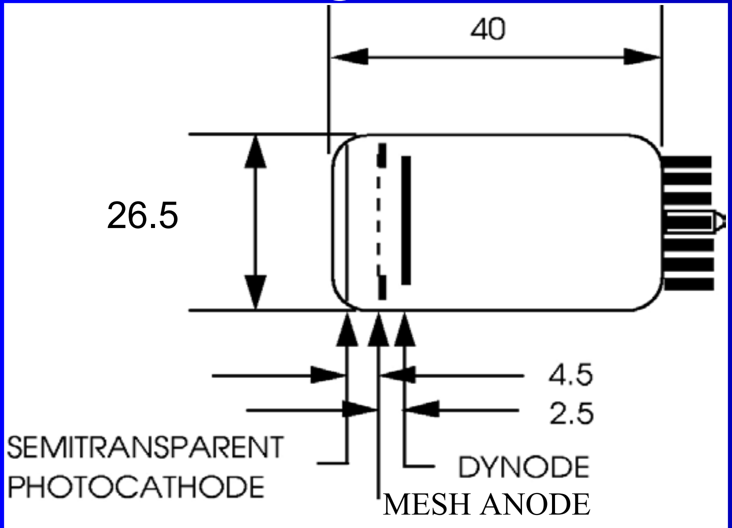
Batch of 18,000 APDs expected by end February 2003.

R&D, prototyping and production done in collaboration with Hamamatsu was so far very positive and successful.

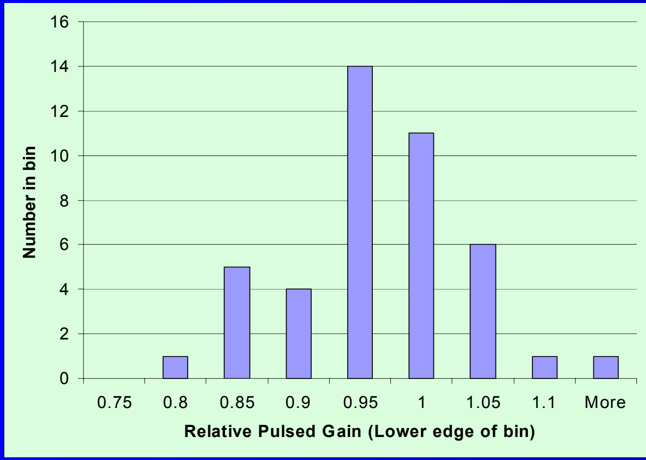
In recognition of these achievements the CMS Collaboration will give the CMS Award 2003 to Hamamatsu on February 24, 2003.

CMS Photosensors for Endcaps:
Vacuum Photo Triodes (VPTs)

Single stage photomultiplier tube with fine metal grid anode



- **B-field orientation favourable for VPTs (Axes: $8.5^o < |\theta| < 25.5^o$ wrt to field)**
- **More radiation hard than Si diodes (with UV glass window)**
- **Gain 8 -10 at B = 4 T**
- **Active area of ~ 280 mm^2/crystal**
- **Q.E. ~ 20% at 420 nm**
- **<10 % decrease in response after 10 years of operation**



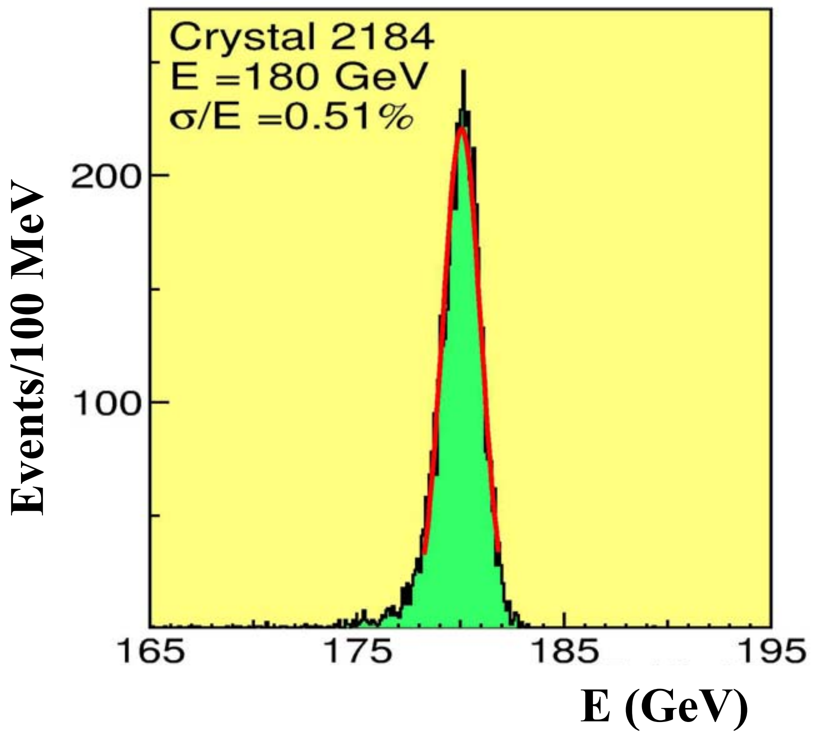
Gain (4 Tesla)
Gain (0 Tesla)

About 3500 VPTs delivered – good quality

Measured Energy Resolution

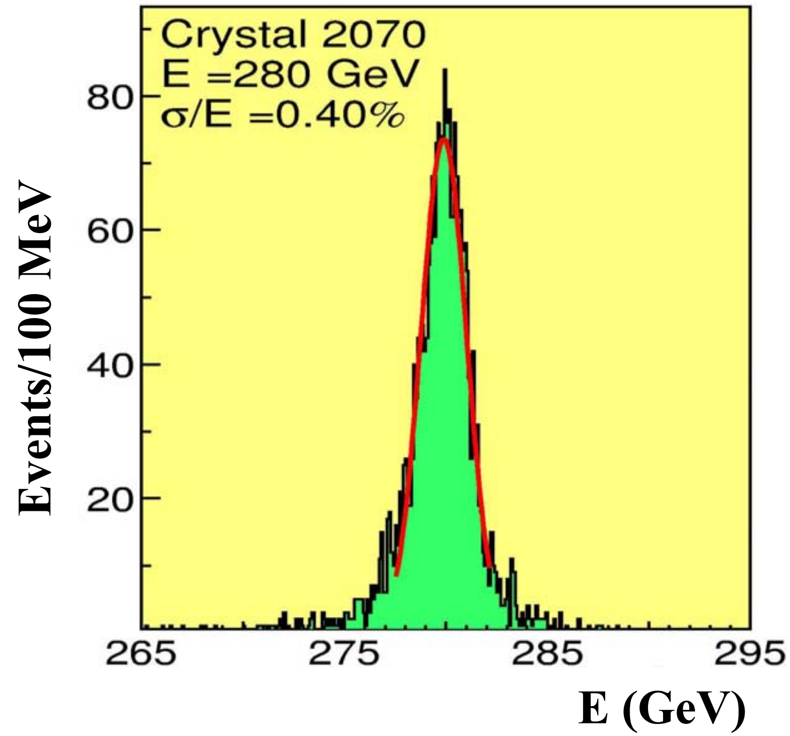
Barrel - 3x3 crystals

$$\frac{\sigma_E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus \frac{140\text{ MeV}}{E} \oplus 0.4\%$$



Endcap - 3x3 crystals

$$\frac{\sigma_E}{E} = \frac{4.1\%}{\sqrt{E}} \oplus \frac{140\text{ MeV}}{E} \oplus 0.25\%$$



Measured energy resolution (slightly better) as expected.

ECAL: Summary and Conclusions

After many years of specialized R&D in close collaboration with expert companies crystal and photosensors production is progressing well and according to schedule. However, some financial constraints bring production of endcap crystals on the critical path.

Electronics is presently undergoing a substantial review. The selection of the components is scheduled for the middle of this year.

Mechanical structures for the barrel are in production and are being delivered according to schedule. About half of the mechanical elements for the endcaps are ordered.

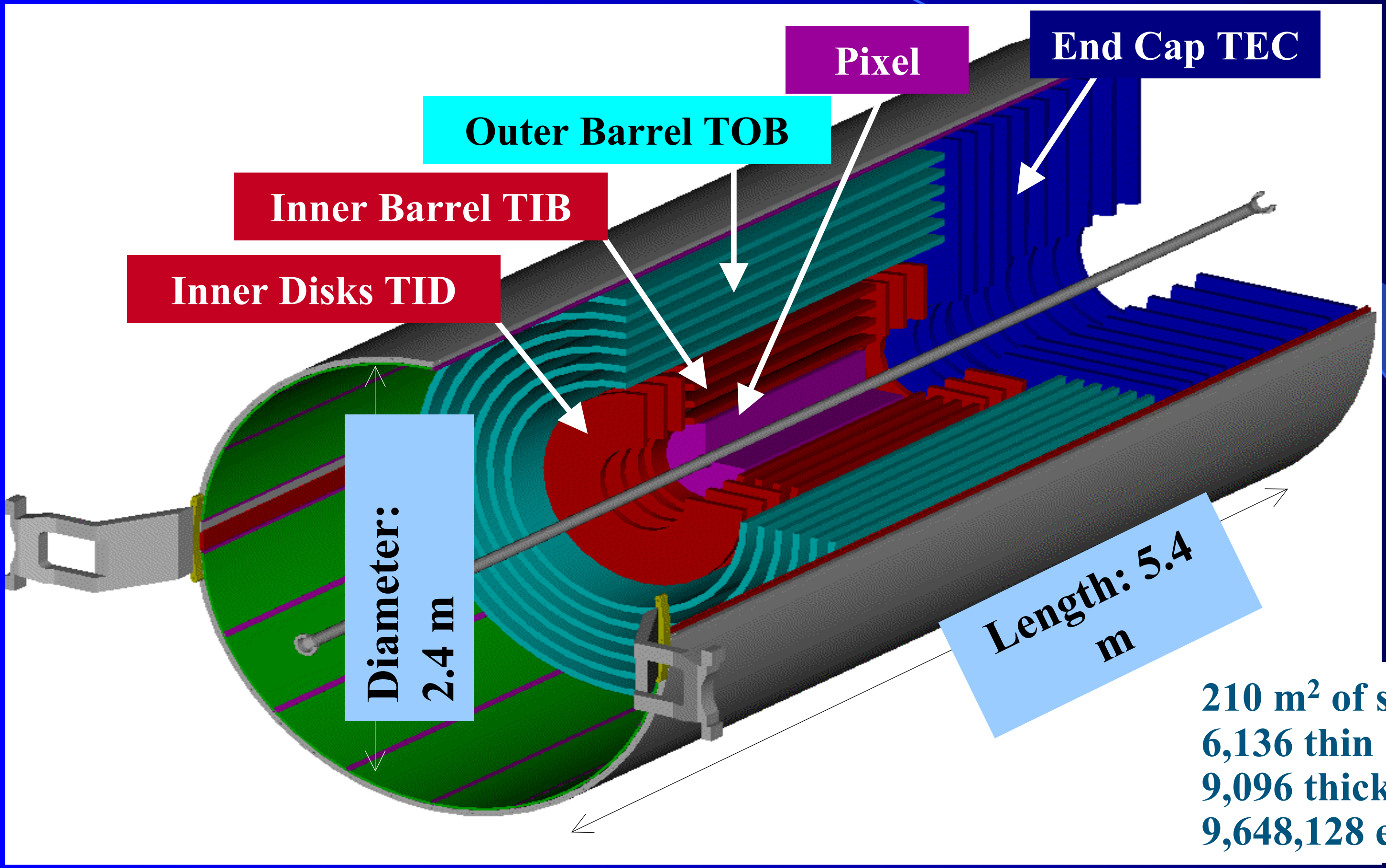
The monitoring system will be complete and operational by the end of 2003.

The Preshower construction is entirely integrated in the construction of the crystal calorimeter and both schedules are synchronized.

Installation procedures and cable routing are being finalized.

The Inner Tracker

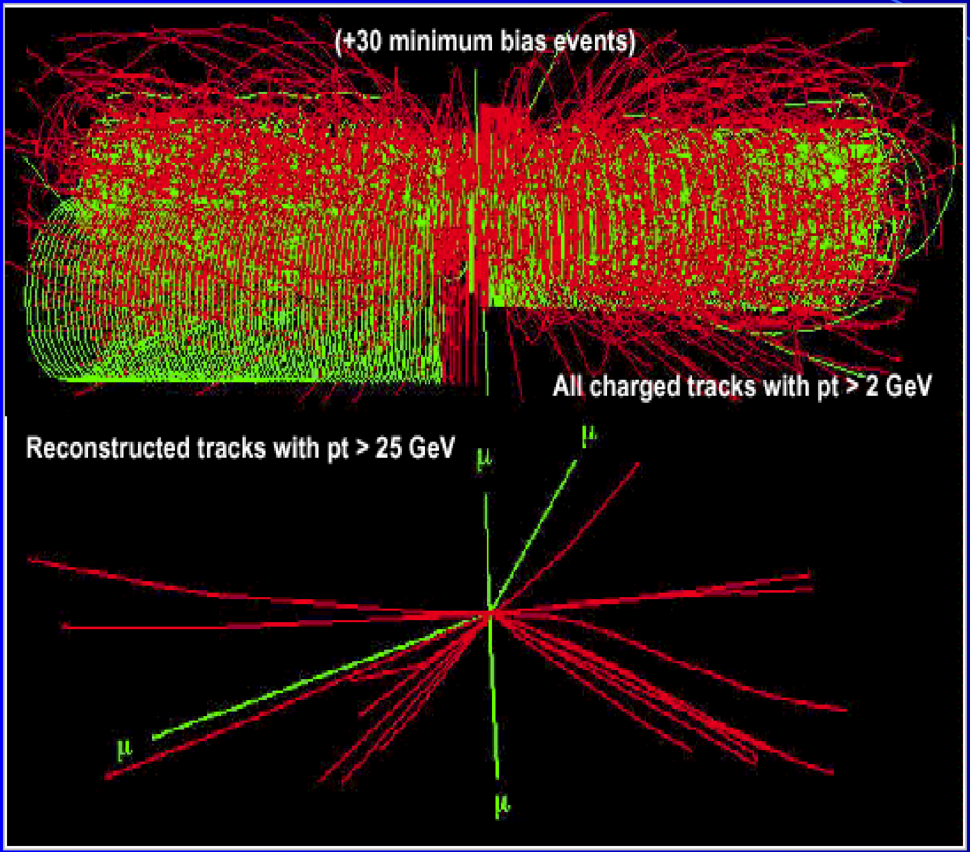
By far the largest device of its kind so far



210 m^2 of silicon sensors
6,136 thin detectors (1 sensor)
9,096 thick detectors (2 sensors)
9,648,128 electronics channels

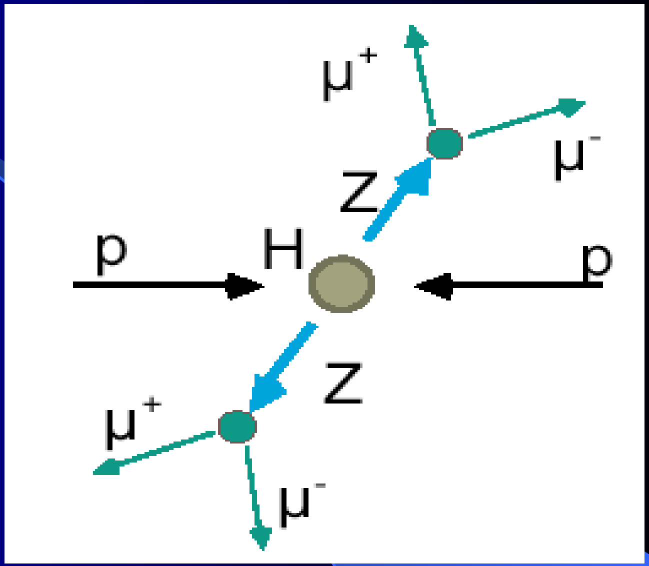
Challenges: Huge number of silicon detectors – “Low” mass – Alignment – Rad-hard modules and electronics - Cooling

Tracker Requirements



pp & high luminosity => "mess"

"Golden Channel"



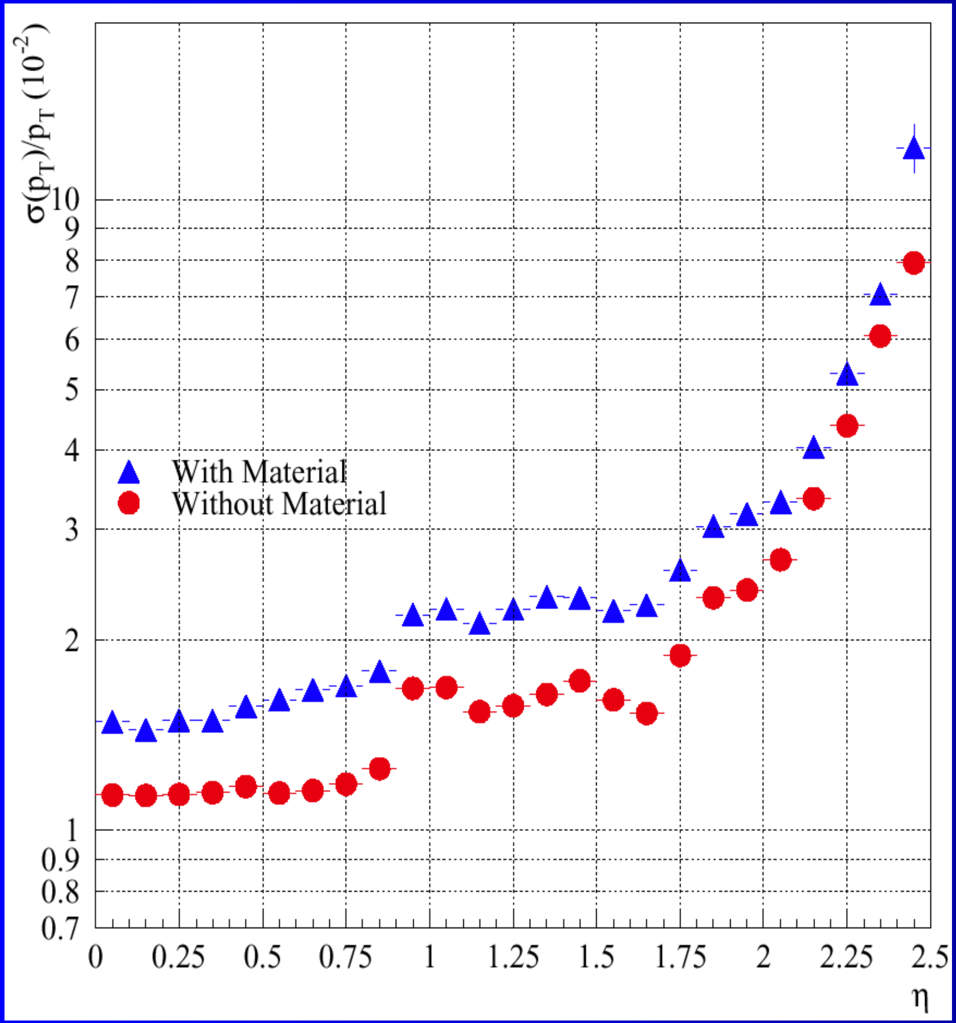
Tracker Requirements:

Ability to reconstruct narrow heavy object
⇒ 1~2% p_t resolution at ~ 100 GeV

Ability to tag b/t through secondary vertex
⇒ Good impact parameter resolution

Efficient & robust pattern recognition algorithm
⇒ Fine granularity to resolve nearby tracks
⇒ Fast response time to resolve bunch crossings

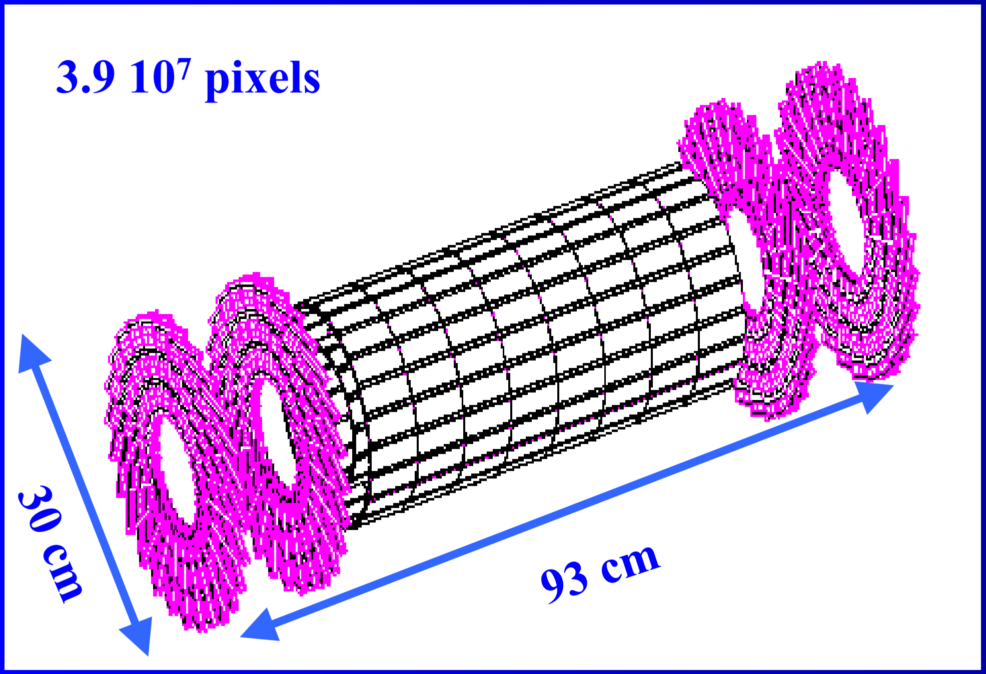
p_t Resolution for High Momentum Muons



The CMS Tracker provides
~ 1% p_t resolution up to η ~ 0.90
~ 2% p_t resolution up to η ~ 1.75
for 100 GeV muons

Impact Parameter Resolution
CMS Pixel Vertex Detector

The region below 20 cm is instrumented with Silicon Pixel Vertex systems



The Pixel area is driven by FE chip

The shape is optimized for resolution

CMS pixel size ~ 150 * 150 mm^2

With this cell size:
$IP_{trans.}$ resolution ~ 20 μm
for tracks with p_t ~ 10GeV

14 192 chips

shaping time ~ 25 ns

occupancy is ~ 10^{-4}

This makes Pixel seeding the fastest starting point for track reconstruction despite the extremely high track density

Design Considerations
Cell Size and Strip Pitch

Efficient & clean track reconstruction is ensured provided occupancy below few %.

At small radii need cell size less than $1cm^2$.
This condition is relaxed at large radii.

$\Delta P_t / P_t \sim 0.1 * P_t$ (P_t in TeV) allows to reconstruct Z to m^+m^- with $\Delta m_Z < 2$ GeV up to $P_t \sim 500$ GeV

Twelve layers with (pitch/ √ 12) spatial resolution and 110 cm radius give a momentum resolution of

$$\frac{\Delta p}{p} \approx 0.12 \left(\frac{\text{pitch}}{100\,\mu\text{m}}\right)\left(\frac{1.1\text{m}}{\text{L}}\right)^2\left(\frac{4\text{T}}{\text{B}}\right)\left(\frac{\text{p}}{\text{Tev}}\right)$$

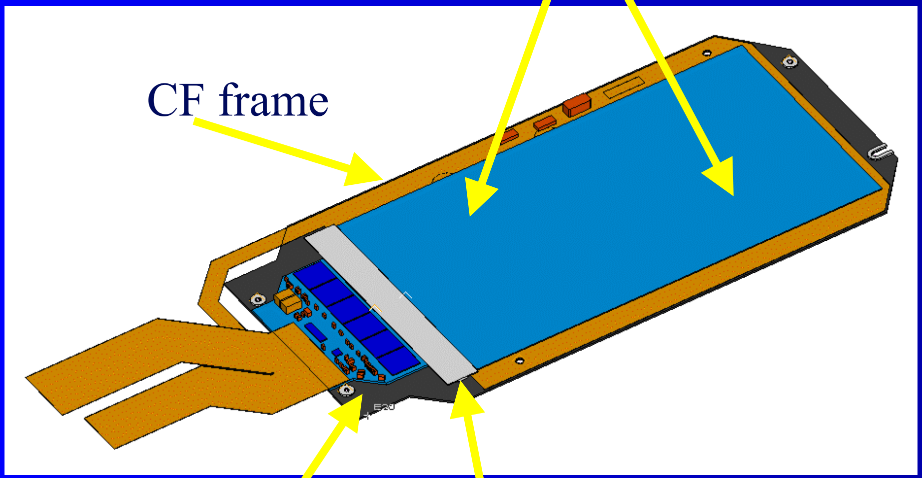
A typical pitch of order 100 mm is required in the phi coordinate to achieve the required resolution.

Strip length ranges from 10 cm in the inner layers to 20 cm in the outer layers.

Pitch ranges from 80 mm in the inner layers to near 200 mm in the outer layers.

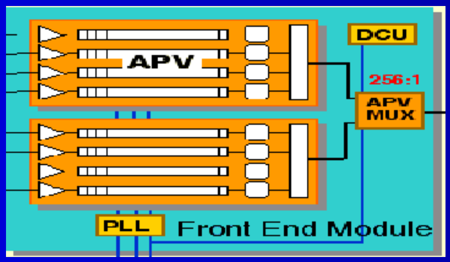
Silicon Detector Module Components

Silicon sensors



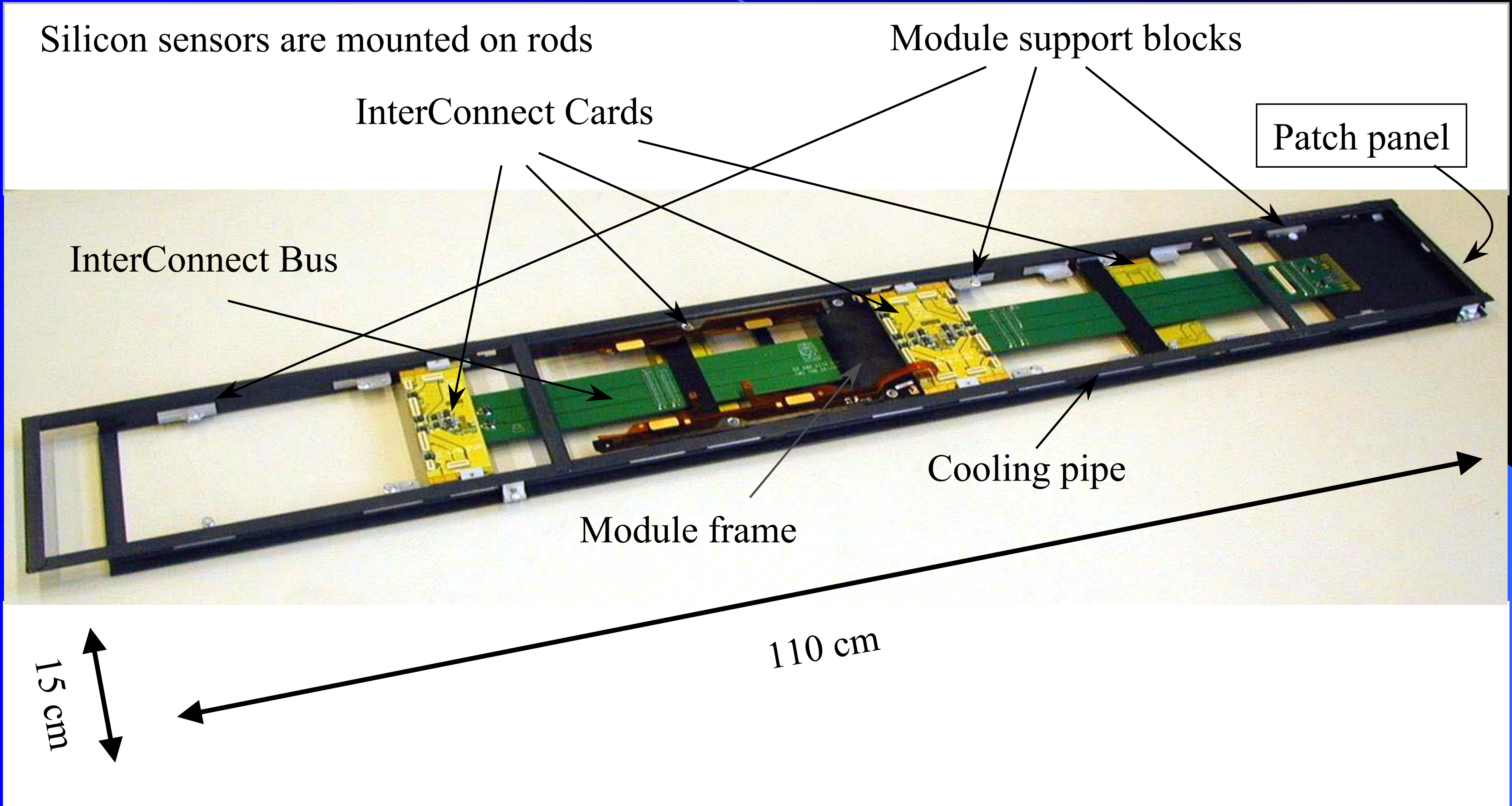
FE hybrid with FE ASICS

Pitch adapter



- 6,136 Thin sensors
- 18,192 Thick sensors
- 6,136 Thin detectors (1 sensor)
- 9,096 Thick detectors (2 sensors)
- 3112 + 1512 Thin modules (ss +ds)
- 5496 + 1800 Thick modules (ss +ds)
- 9,648,128 strips ≡ electronics channels
- 75,376 APV chips
-
- 25,000,000 Bonds
- 440 m^2 of silicon wafers
- 210 m^2 of silicon sensors ($162m^2 + 48m^2$)

Silicon Assembly



Silicon Sensors from Two Producers

ST Microlectronics, Italy

Type	Received
OB2	908
OB1	186
W6a	19
TOTAL	**1113**

Hamamatsu, Japan

Type	Received
IB1	79
IB2	70
W2	45
W3	42
W4	50
TOTAL	**286**

In total CMS has already received 1399 sensors.
Qualification and production according to schedule.

Silicon Sensor Quality Control

Sensors from Hamamatsu:

Excellent quality (only 1 sensor rejected).
Nearly 100% sensor acceptance.

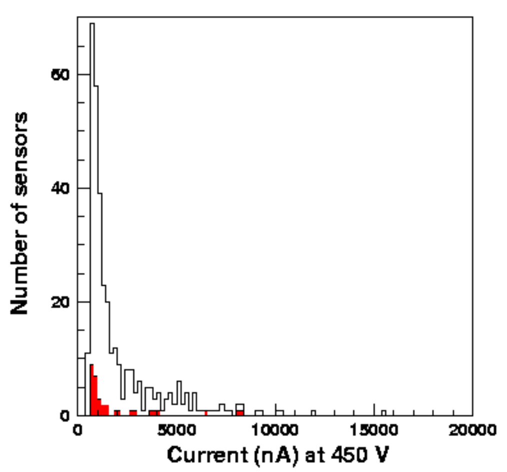
Sensors from ST Microelectronics:

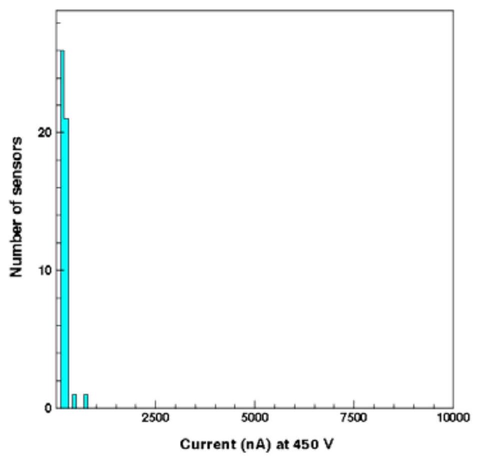
Problem with mechanical quality. Many damaged and broken sensors.
Electrical quality seems ok.
Sensor are also rejected due to electrical failures, but most likely this is correlated with poor mechanical quality.
Overall rate of acceptance about 60%.

A new production flow, avoiding unnecessary manual handling, was defined.
In addition, several quality control gates are introduced at ST to prevent shipment of damaged sensors.

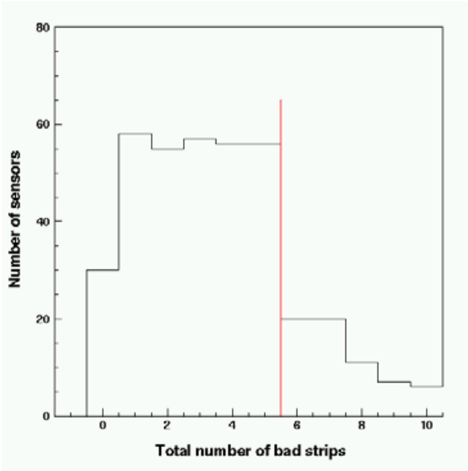
Quality Testing

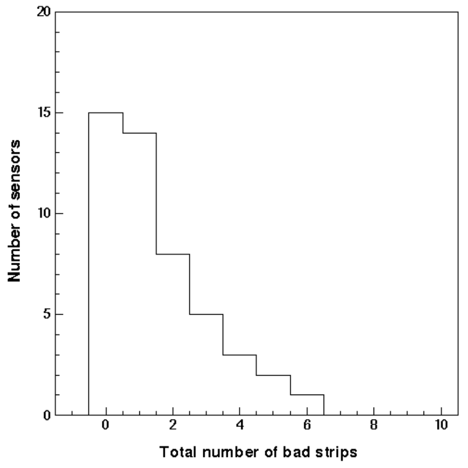
Total current at 450 V





Number of bad strips

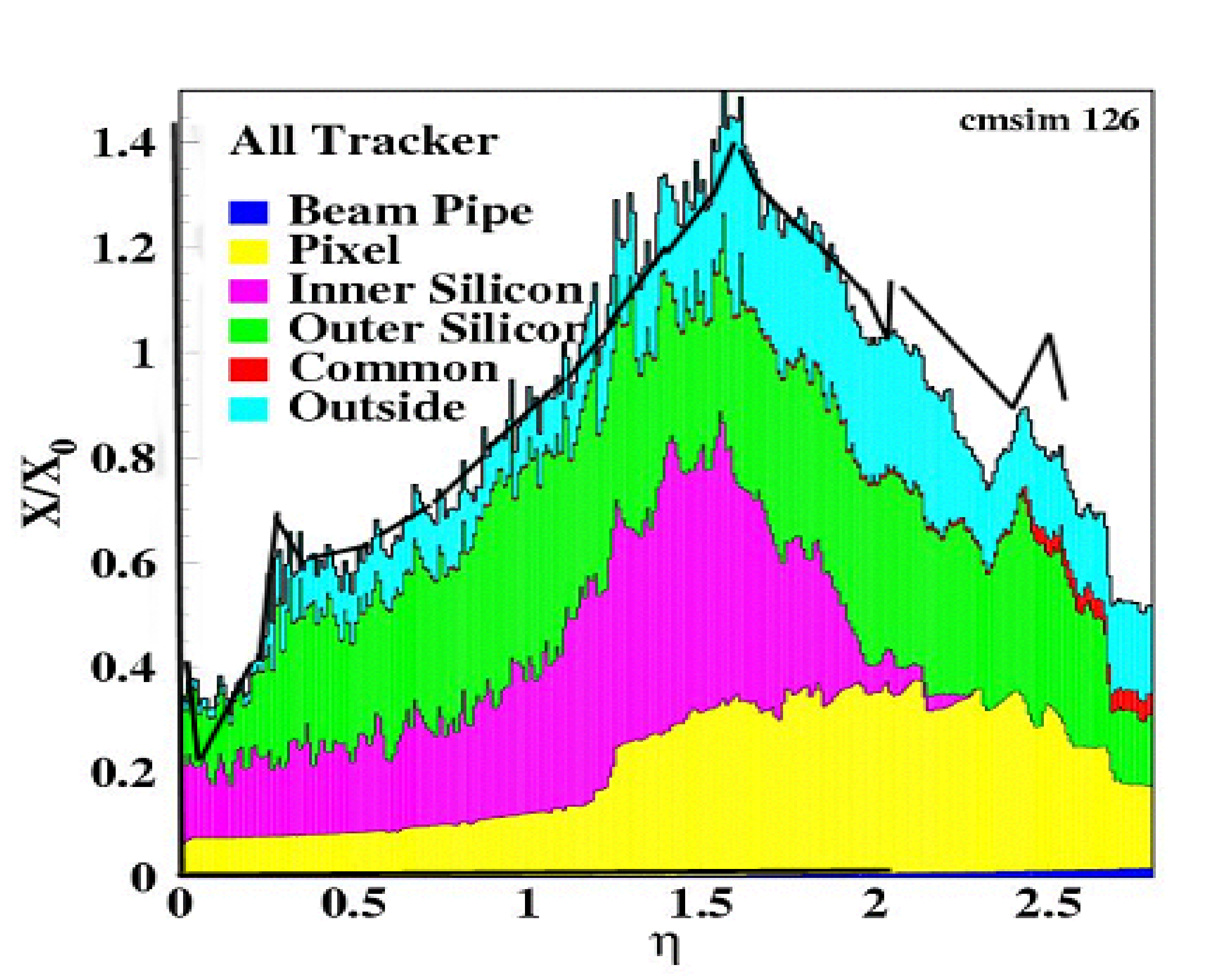




ST Microelectronics

Hamamatsu

Tracker Material Budget



Tracker: Summary and Conclusions

- The pixel vertex detector allows fast & efficient track seed generation, as well as excellent 3-D secondary vertex identification
- The fine granularity of the pixel and strip sensors, together with the analyzing power of the CMS 4T magnet allow for a ~ 2% or better p_t resolution for 100 GeV muons over about 1.7 units of rapidity
- The CMS Silicon Tracker has robust performance in a difficult environment
- A good determination of track parameters with only a few hits (4~6) allows fast and clean pattern recognition
- The construction of all major components is on schedule

Hadron Calorimeter

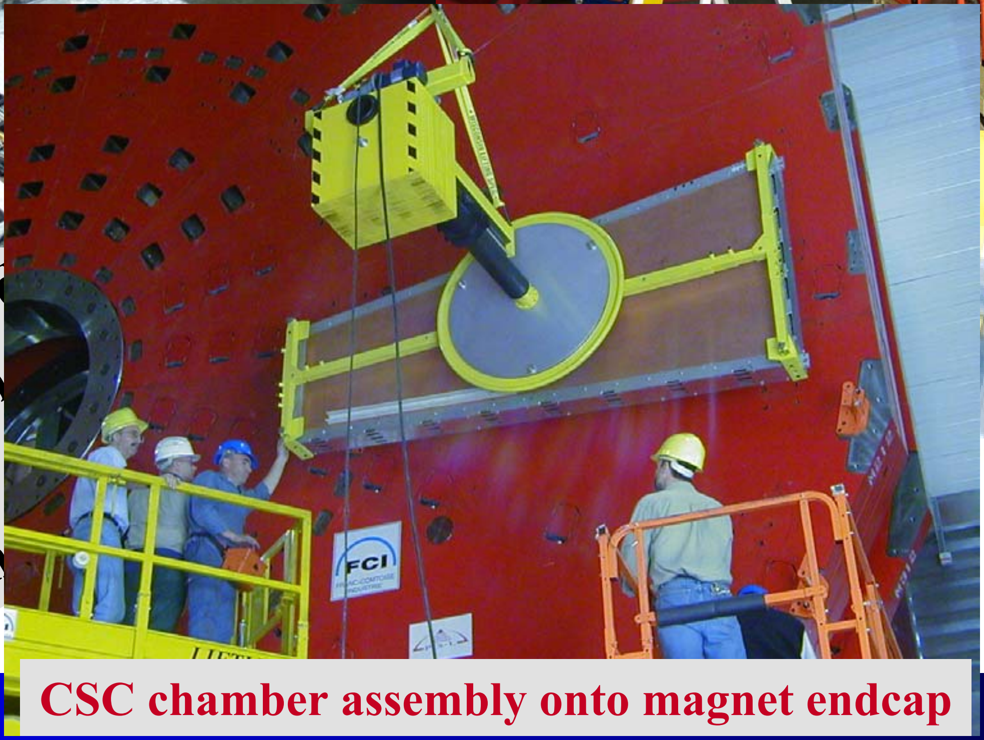
Hadron Calorimeter Barrel Mechanics Completely Assembled at Exp. Area.

First Hadron Calorimeter Endcap Mechanics Assembled at Magnet.

Muon Detector


DT chamber production in Aachen


DT chamber insertion into magnet barrel


CSC chamber assembly onto magnet endcap

CMS Awards to Industry

Starting from the year 2000 the CMS Collaboration is honoring industry who have made outstanding contributions to the construction of the experiment with the

CMS Gold Award.

Companies who have demonstrated their excellence and engagement and who provide parts within specifications and on schedule are considered for this award.

Firms who, in addition, have made special efforts and taken initiative to work out technically and/or commercially better products are honored with the

CMS Crystal Award.

Companies who have explored novel technologies and collaborated in R&D programs with CMS are candidates for this award.

CMS Gold Awards

		Project
2000	- Izhorskiye Zavody (Kolpino, Russia) - ZDAS (Zdar nad Sazavou, Czech Republic)	Thick Forged Iron Plates for Magnet Barrel Design & Casting of Iron Brackets for Magnet
2001	- Superbolt Inc. (Carnegie, USA) - Hudong Heavy Machinery (Shanghai, China)	Special Bolts for Endcap Disks Production of Endcap Carts for Endcap Disks
2002	- André Laurent SA (La Ricamarie, France) - Noell Konecranes (Langenhagen, Germany) - Kabelwerke Brugg (Brugg, Switzerland) - Alcan Aluminium Valais (Sierre, Switzerland) - Sumitomo Chemicals (Ethime, Japan)	Special Tie Bars for Barrel Yoke Manufacture of Air Pad System Manufacture of Superconduct. Cable Extrusion of High Qual. Alumin.Alloy High Purity Aluminium
2003	- Res. Inst. for Techn. Phys. (Snezhinsk, Russia) - Dembiermont (Hautmont, France) - EAE Machinery Corp. (Istanbul, Turkey) - Franc-Comtoise Ind. (Lons-le-Saunier, France -Makine Freze Kalip Ltd. (Bursa, Turkey) -Myasishchev (Zhukovsky, Russia) - MZOR (Minsk, Belarus) - NIKIET (Moscow, Russia)	Wedges for Forward HCAL Seamless Rings and Shoulders for Coil Strongback Components for Forward HCAL Assembly of the CMS Magnet Strongback Components for Forward HCAL Alveolar Structures for CMS ECAL Mechanics for HCAL Endcaps Mechanics for HCAL Endcaps

CMS Crystal Awards

		Project
2000	- Deggendorfer Werft & Eisenbau (Deggendorf, Germany)	Manufacture of Magnet Barrel Yoke
2001	- Felguera Construcciones Mecanicas (Barros, Spain)	Manufacture HCAL Barrel
	- Kawasaki Heavy Industries (Harima, Japan)	Manufacture of Magnet Endcap Disks
2002	- Nexans Suisse SA (Cortaillod, Switzerland)	Co-Extrusion Process
	- Outokumpu Pori Oy (Pori, Finland)	High Quality Superconducting Strands
	- Plascore Inc. (Zeeland, USA)	High Prec. Panels for Muon Detector
2003	- Doosan Heavy Industry (Changwon, Korea)	Swivelling Platform
	- Hamamatsu Photonics (Hamamatsu, Japan)	Radiation Hard APDs
	- Polymicro (Phoenix, USA)	Radiation Hard QP Fibres
	- Techmeta (Pringy, France)	Reinforcement of Inserts

Conclusions

The construction of the CMS Experiment requires the development and application of novel technologies.

The size and complexity of the experiment calls for involving experienced and dedicated industry from all over the world.

Physicists and engineers from participating institutes collaborate closely with industry to achieve the required performance of components for CMS.

Over the last years puzzles and problems arose and solutions were found.
In some cases financial difficulties were problematic.
They could be resolved by changing scope or alternative solutions.

More than 50% of the total estimated cost have been spent,
about 70% are committed.

CMS construction is progressing according to schedule and
plans to manage financial difficulties (about 50 MUSD missing)
are receiving support by the Funding Agencies.
The detector will be ready for the first physics runs in 2007.